AD-A033 337 ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MISS F/G 13/2
LIQUEFACTION POTENTIAL OF DAMS AND FOUNDATIONS, REPORT 1. LABOR--ETC(U)
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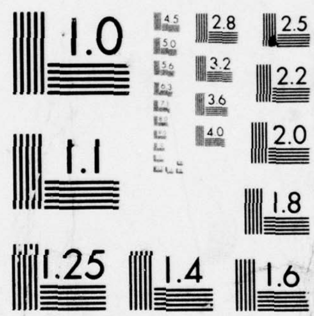

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RESEARCH REPORT S-76-2

LIQUEFACTION POTENTIAL O AND FOUNDATIONS

Report 1

LABORATORY STANDARD PENETRATIO REID BEDFORD MODEL AND OTTAW

by

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October 1976

Report 1 of a Series

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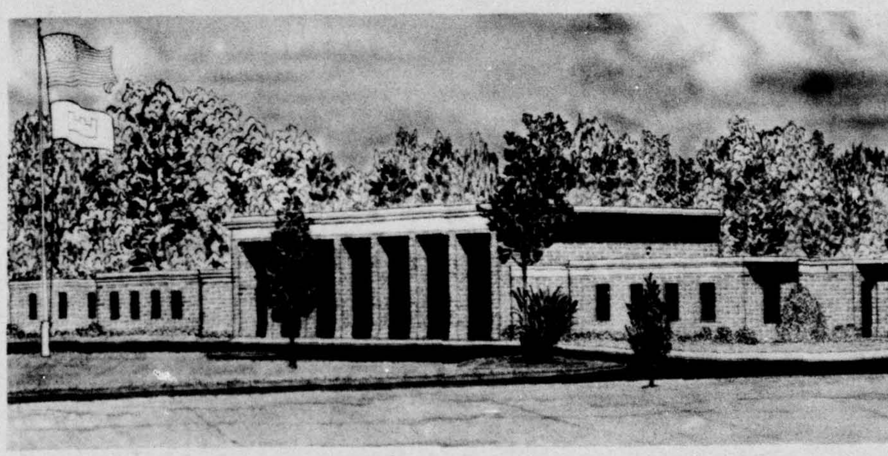

Prepared for Office, Chief of Engineers, U. S.
Washington, D. C. 20314

Under CWIS 31145

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 9 Research Report S-76-2	2. GOVT ACCESSION NO. 14 WES-RR-S-76-2	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (*and Subtitle*) 6 LIQUEFACTION POTENTIAL OF DAMS AND FOUNDATIONS. Report 1. LABORATORY STANDARD PENETRATION TESTS ON REID BEDFORD MODEL AND OTTAWA SANDS.		5. TYPE OF REPORT & PERIOD COVERED Report 1 of a Series
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 Wayne A. Bieganousky William F. Marcuson, III		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Soils and Pavements Laboratory P. O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS CWIS 31145
11. CONTROLLING OFFICE NAME AND ADDRESS Office, Chief of Engineers, U. S. Army Washington, D. C. 20314		12. REPORT DATE 11 Oct[redacted]76
		13. NUMBER OF PAGES 156
14. MONITORING AGENCY NAME & ADDRESS(*if different from Controlling Office*) 12 159p.		15. SECURITY CLASS. (*of this report*) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Dams	Sands
Foundations	Soil tests
Liquefaction (soils)	Standard Penetration Test
Relative density	

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

The Standard Penetration Test (SPT) is critically examined with respect to its ability to estimate relative density in situ. A review of the literature tracing the development of the SPT is presented. Twenty-six (26) test specimens, 4 ft in diameter by 6 ft high, were constructed using Reid Bedford Model sand and Ottawa sand. A variety of placement techniques were incorporated in the test program. The problems encountered in constructing large homogeneous test specimens are discussed. Using field drilling equipment, the SPT was

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Unclassified

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20. ABSTRACT (Continued).

performed at three overburden pressures on test specimens built to various densities. The results are presented as a family of curves correlating relative density with the SPT N-values at the testing pressures. This correlation is compared with correlations prepared by Gibbs and Holtz at the Bureau of Reclamation and Bazaraa at the University of Illinois. It is concluded that the SPT is fairly repeatable in homogeneous deposits; however, variations in density, structure, or lateral stress within the test medium will produce widely scattered N-values. Thus, estimates of in situ relative densities from N-values should be considered gross values or trends and should not be interpreted as accurate determinations for any specific case.

PREFACE

The study reported herein was performed by the U. S. Army Engineer Waterways Experiment Station (WES) as part of the Office, Chief of Engineers (OCE), Civil Works Research effort. This investigation was authorized by OCE under the CWIS 31145 work unit entitled "Liquefaction Potential of Dams and Foundations."

WES engineers who were actively engaged in this study were Dr. W. F. Marcuson III and Messrs. S. S. Cooper, J. R. Horn, and W. A. Bieganousky. The work was conducted under the general supervision of Messrs. R. W. Cunny and W. C. Sherman, Jr., former Chiefs, Earthquake Engineering and Vibrations Division (EE&VD), and Dr. F. G. McLean, Chief, EE&VD, and Mr. J. P. Sale, Chief, Soils and Pavements Laboratory. This report was prepared by Messrs. W. A. Bieganousky and W. F. Marcuson III and reviewed by Mr. S. J. Johnson, Dr. F. G. McLean, and Professor J. H. Schmertmann.

During the conduct of this study and the preparation and publication of this report, BG E. D. Peixotto, CE, COL G. H. Hilt, CE, and COL J. L. Cannon, CE, were Directors of WES. Technical Director was Mr. F. R. Brown. OCE technical monitor of this study was Mr. R. W. Beene.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
feet	0.3048	metres
pounds (mass)	0.4535924	kilograms
pounds (force)	4.448222	newtons
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force) per square inch	6894.757	pascals
kips (force) per square foot	47.88026	kilopascals
degrees (angular)	0.01745329	radians

LIQUEFACTION POTENTIAL OF DAMS AND FOUNDATIONS

LABORATORY STANDARD PENETRATION TESTS ON REID BEDFORD MODEL AND OTTAWA SANDS

PART I: INTRODUCTION

Background

1. The potential for liquefaction of a cohesionless soil is related to the intensity of dynamic loadings, the in situ stresses, the grain size characteristics of the soil, the shear strength, and in place density.[1] Essential to the art of predicting the dynamic response of a site is the matter of obtaining high quality samples for testing and classification. This is a difficult task when cohesionless materials are encountered; it is made more difficult by the presence of groundwater.

2. The procurement of high quality samples of submerged cohesionless soils has been accomplished using freezing techniques. Although successful in the sense of retrieving samples, the process is expensive. A thin-walled fixed-piston Hvorslev[2] type sampler was used by the U. S. Army Engineer Waterways Experiment Station (WES) for the express purpose of taking high quality undisturbed sand samples in the late 40's. WES found that retrieval of a sample was aided by drilling mud and the vacuum created by a stationary piston. Relatively undisturbed samples can be obtained from substantial depths below the water table by this technique.[3]

3. Other samplers capable of obtaining high quality samples have evolved, each with their own peculiarities. These samplers are widely used in some areas, and virtually unknown in others. A drawback of the use of these samplers is the considerable expense involved.

4. More popular than undisturbed samplers is the Standard Penetration Test (SPT). The test development and early use are attributed to the Gow Company of Raymond Concrete Pile Co.,[4] and were reviewed by

Terzaghi.[5] It consists of driving a split barrel sampler (split spoon as it is commonly known) 18 in.* into the ground with a 140-lb hammer falling through 30 in. of drop. The number of blows required to drive the split barrel in three 6-in. increments is recorded, and the last two incremental values are added to obtain the number of blows per foot. This value is commonly referred to as the N-value and represents the penetration resistance of the material under test.

5. Investigation of this test in the early 1950's by Gibbs and Holtz at the Bureau of Reclamation resulted in a family of curves which allowed an estimate of the relative density of a cohesionless material to be made from the recorded penetration resistance.[6] Their research showed conclusively that penetration resistance was a function of relative density and overburden pressure. Hence, a quick estimate of the in situ relative density of a given site could be obtained easily, and many engineers have employed the Gibbs and Holtz correlation curves in practice.

6. A similar family of curves relating penetration resistance to relative density was developed by Bazaraa based on empirical data. These curves exhibited a higher degree of conservatism.[7]

7. The Hvorslev fixed-piston undisturbed sampler and the SPT are frequently employed as a means of estimating in situ densities for liquefaction studies. The reliability of these two techniques is of major concern; hence, the Corps of Engineers research program investigating the phenomenon of liquefaction has included a study to evaluate the effectiveness of the Hvorslev fixed-piston undisturbed sampler and the SPT in obtaining representative values of in situ density.

Purpose

8. One objective of this research study is to improve the Corps of Engineers ability to determine in situ density and relative density,

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 6.

or develop some other index more reliably related to liquefaction potential. This report describes the results of a full-scale laboratory test program performed to investigate the viability of the SPT as an index for liquefaction potential of cohesionless materials, through the relative density concept.

Scope

9. At the outset of this study these questions were asked: Can accurate relative and absolute density determinations be made for loose cohesionless material? Should a new index be developed for relating in situ density to liquefaction behavior?

10. It was believed that these questions could be answered after: (a) reviewing current work and literature on relating penetration resistance to density or relative density, (b) making empirical correlations between field behavior, penetration resistance, soil properties, and other characteristics as an independent means of assessing liquefaction potential, and (c) conducting a series of laboratory tests with the (1) SPT, (2) Hvorslev fixed-piston undisturbed sampler, (3) rotary cone, and (4) Dutch cone to evaluate their performance.

11. This report presents a summary of the literature review and the results of penetration testing on two sands, Reid Bedford Model and Ottawa sands, accomplished in the laboratory. The laboratory program, when completed, will encompass two additional sands, Platte River and Standard Concrete sands.

12. During the conduct of many of the SPT's, undisturbed samples were taken with the Hvorslev fixed-piston sampler. These samples were carefully handled to keep disturbances to a minimum. Each sample was transversely cut in sections with a band saw, and incremental density determinations were made. A comparison between the incremental tube densities and the density of the test specimen provided a vehicle for an evaluation of the sampler. The results of the undisturbed sampling are presented in Reference 8.

PART II: LITERATURE REVIEW

13. This literature review traces the development of the SPT as a procedure for determining in situ density. It is not meant to be an exhaustive work, but a summary of previous systematic research and the current direction of SPT usage. A recent comprehensive bibliography pertaining to all aspects of the SPT can be found in de Mello's[9] state-of-the-art report.

14. The practice of retrieving dry samples appeared first in 1902, introduced by COL Charles R. Gow,[4] and consisted of driving a 1-in.-diam open-end pipe into the soil. Procedural improvements occurred with the development of the 2-in.-diam split spoon, and the standardization of the 140-lb hammer and 30-in. drop. Known internationally as the Standard Penetration Test, the initial development is credited to engineers of the Gow Company, a subsidiary of the Raymond Concrete Pile Company, in the late 1920's.

15. In 1952, the Bureau of Reclamation conducted a study to examine the influence of various factors on the SPT.[10] The variables included density, moisture content, overburden pressure, and length and weight of the drill rod. The test program was conducted in the laboratory using field sampling equipment and a cylindrical soil container, approximately 3 ft in diameter by 4 ft high. Overburden pressure was applied by means of loading plates and springs. The results reported were derived from testing a well graded coarse to fine sand.

16. The results showed that penetration resistance increased as a result of increases in density and overburden pressure. The study further showed that increasing the length of the rod tended to increase the recorded penetration resistance in dense and very dense sands, and decrease the N-values for loose and medium densities. The B-size rod displayed the least effect and was recommended over the A- and N-rods. The effect of rod weight was studied; however, at the time of the report the data were too scarce to be conclusive. The degree of saturation and its effect on the SPT N-values were also studied. It was observed that increasing moisture content had only a slight effect on penetration

resistance, trending toward lower resistance values for higher moisture contents.

17. In 1957 Gibbs and Holtz[6] published the results of their completed study on the SPT. The penetration resistance was shown to increase with an increase in either relative density or overburden pressure. Several plots were presented which depicted these relationships for coarse and fine sands, both in air-dry and submerged states. A single family of curves was recommended based on the results of the air-dry tests on the coarse and fine sands. The results derived from testing submerged sands were not considered reliable because it was doubtful that the laboratory setup accurately represented a water table condition. The study determined that increasing the length of rod had a relatively small effect when compared to overburden pressure effects. Similarly, the effect of rod weight was small when compared to overburden pressure, especially for dense sands. Loose sands displayed lower blow counts as a result of increased rod weight.

18. Palmer and Stuart[11] were in general agreement with the findings of Gibbs and Holtz[6] concerning the effect of rod length and weight on the N-values of the SPT. An analysis of the stresses set up in the rods as a result of hammer impact showed that from a depth of 5 to 20 ft, the stresses fall by about 35 percent, and thereafter remain almost constant. This suggests that the value of N may not be influenced substantially when the length of the rods is over 20 ft. Palmer and Stuart also stated that the ratio of the weight of rods in relation to the impact forces is very low; therefore, the length and weight of rods are not likely to have much influence on the N-value, except in extremely soft or loose ground.

19. Kolbuszewski[12] presented data illustrating the influence of relative porosity and grain size distribution on the SPT N-values. The results of his study indicated that these two variables must be considered, as the effects are substantial. The different techniques used for determining the maximum and minimum densities of a sand were also discussed; Kolbuszewski recommended that the minimum density be determined by pouring the sand through water rather than pouring through air.

20. Coffman,[13] 1960, published a chart based on the Gibbs and Holtz recommended curves which simplified the determination of the relative density. Coffman found the chart "best satisfied other checks" in the range of 65 to 95 percent relative density, and presented a mathematical relationship for this range in terms of relative density, overburden pressure, and penetration resistance:

$$D_{R_{65\ to\ 95}} = 40 + 7.19\left[\frac{7.36(N - 2.4)}{\sigma_v + 1.36} - 17.9\right]^{1/2}$$

where

$D_{R_{65\ to\ 95}}$ = relative density, in percent, between 65 and 95 percent

N = number of blows per foot from the SPT

σ_v = vertical overburden pressure, kips/ft^2

Coffman recommended correlation tests on sensitive projects.

21. In 1961, Schultze and Menzenbach[14] published relationships between the SPT N-value and the compressibility of soils. The authors conducted a program of study involving the correlation between penetration resistance recorded in situ and laboratory confined compression tests performed on undisturbed samples taken from the same locations. The results of 225 pairs of data analyzed using statistical methods were presented in the form of:

$$E_s = \frac{1}{m_v} = C_1 + C_2 \cdot N \pm S_E$$

where

E_s = modulus of compressibility

m_v = coefficient of compressibility

C_1, C_2 = constants which depend on soil type

N = standard penetration value, blows per foot

S_E = standard deviation of observation

They found that it was possible to show a relationship between the modulus of compressibility and penetration resistance for 12 different

cohesive and noncohesive soil groups. This correlation had a standard deviation of ± 25 percent if pore water pressure did not influence the results of the penetration tests.

22. In the course of their study, Schultze and Menzenbach examined the relationship between penetration resistance, overburden pressure, and relative density. Using statistical methods they developed a correlation comparable to that developed by Gibbs and Holtz.[6] They found for sandy soils that the relationship could be represented by the following equation:

$$\log_e D_R = 0.478 \log_e N - 0.262 \log_e \sigma_v + 2.84$$

where

D_R = relative density

N = standard penetration resistance

σ_v = overburden pressure

The results gave a coefficient of correlation of 0.87 with a standard deviation of 4.1 percent.

23. In 1963 Thorburn[15] published a tentative correction chart for the SPT in noncohesive soils. Thorburn used Gibbs and Holtz's[6] work and a limited number of plate loading tests to construct a correction chart correlating penetration resistance, overburden pressure, and relative density. His chart could be used to correct N-values for overburden pressure, thus obtaining corrected N-values which could be used to enter the Terzaghi and Peck[5] settlement charts.

24. Fletcher[4] published a paper relating the historical development of the SPT and some common abuses of the test. According to Fletcher, the test "provides an indispensable yardstick of soil properties" and it was the improper use of methods and equipment which made the SPT results unreliable. He listed the following as important factors affecting the SPT results:

"1. Inadequate cleaning of the borehole;

2. failure to maintain sufficient hydrostatic head in the boring;

3. variations from an exact 30-in. drop of the drive weight;
4. use of drill rods heavier than 1-in. extra heavy pipe or A rods;
5. extreme length of drill rods (over 175 ft);
6. interference with free fall of the drive weight from any cause;
7. use of a 140-lb weight without hardwood cushion, block, or guide rod;
8. use of sliding weight that can strike the drive cap eccentrically;
9. use of deformed tip on sample spoon;
10. excessive driving of sample spoon before the blow count;
11. failure to seat sample spoon on undisturbed material;
12. driving of sample spoon above bottom of casing;
13. and carelessness in counting the blows and measuring penetration."

25. Zolkov and Wiseman[16] studied the effect of overburden pressure relief on the SPT in connection with the foundation exploration for a 35-story reinforced concrete structure in Tel Aviv. SPT's were performed in cased holes from the original ground surface, and again following a general excavation of 50 ft of overburden. The soil profile was predominantly clean uniform sands with occasional strata of clayey sands and slightly cemented sands. The removal of the overburden and the overlapping SPT allowed an opportunity to observe the influence of overburden pressure on the SPT results. The test results displayed a reduction in penetration resistance; however, the reduction was not as large as expected. They concluded that the blow count is markedly influenced by the overburden pressure existing at the time of the test, that maximum past overburden pressure is an important consideration in the interpretation of the results, and that residual horizontal stresses associated with overconsolidation are responsible for the higher than expected penetration resistances.

26. Schultze and Melzer[17] claimed that previous penetration resistance studies reported by Schultze and Menzenbach[14] were not reliable due to errors made in the determination of the density. To overcome the

difficulties encountered in the previous study, isotopic soundings (gamma and neutron penetrometers) were used to ascertain the density and moisture content of the test specimen. These tests were run in a soil container 3.3 ft in diameter and 6.0 ft deep. Sand was placed in lifts and vibrated to the desired density. The dynamic penetrometer used was equipped with a 60-deg cone rather than the split spoon sampler.

27. The results of their study were summarized by the following equation:

$$D_R = 0.317 \log N - 0.226\sigma_v + 0.392$$

where

D_R = relative density

N = blow counts per foot of penetration

σ_v = overburden pressure

This formulation is in qualitative agreement with the work of Gibbs and Holtz,[6] i.e., the interrelationship between overburden pressure, SPT N-values, and relative density. Schultze and Melzer also reported, based on observations of SPT's immediately above and below the water table, that the influence of groundwater was to decrease the penetration resistance.

28. Bazaraa,[7] 1967, examined the available correlations relating overburden pressure, relative density, and penetration resistance in his endeavor to develop a corrected settlement chart. He found through comparisons with field data that the existing correlations did not reliably predict field densities. Using the results of many field tests Bazaraa developed a new correlation expressed by the following equations:

$$N = 20D_R^2(1 + 2\sigma_v) \quad \text{for} \quad \sigma_v \leq 1.5 \text{ kips/ft}^2$$

$$N = 20D_R^2(3.25 + 0.5\sigma_v) \quad \text{for} \quad \sigma_v \geq 1.5 \text{ kips/ft}^2$$

where

N = standard penetration test blow counts

D_R = relative density

σ_v = overburden pressure

29. The equations are partly based on the assumption that the Terzaghi-Peck[5] correlation between settlement for 1 in. and N-value corresponds to an effective overburden pressure of about 1.5 $kips/ft^2$ The Bazaraa correlations are more conservative than the Gibbs and Holtz correlations. Bazaraa suggests that the N-values can be corrected for use in settlement correlations by the following equations:

$$N_B = \frac{4N}{1 + 2\sigma_v} \quad \text{for} \quad \sigma_v \leq 1.5 \text{ kips/ft}^2$$

$$N_B = \frac{4N}{3.25 + 0.5\sigma_v} \quad \text{for} \quad \sigma_v \geq 1.5 \text{ kips/ft}^2$$

where

N_B = ($\leq$ 80) = corrected penetration value for overburden pressure

N = penetration value

σ_v = overburden pressure which corresponds to N

30. Bazaraa investigated the effect of submergence on penetration values and found some correction needed. Until further investigations show otherwise, he recommended the Terzaghi-Peck[5] relationship for submerged very fine or silty sand:

$$N = 15 + \frac{1}{2}(N' - 15)$$

where

N = corrected value

N' = recorded value $\geq$ 15

For $N' < 15$, $N = N'$

31. Bazaraa went on to examine penetration resistance values versus settlement correlations and make suggestions based upon field data comparisons with these various correlations. The field data used came from many different sources from all areas of the world. Such being the case, questions have arisen concerning the validity of basing

assumptions on data collected by different organizations, for different purposes, by different techniques.

32. The lack of standardization of the SPT was discussed by Ireland, Moretto, and Vargas[18] in 1970. Ireland and Vargas stated that the test was useful even with its many drawbacks. Vargas strongly advocated greater standardization, while Moretto stated he preferred a modified sampler with interchangeable drive shoes that would be adaptable to different soil conditions. Moretto believed that the experience and past data based on the SPT were highly questionable and therefore, little would be lost in the changeover to a new sampling technique. Ireland and Vargas supported international standardization and adoption of the SPT; Moretto disagreed. The stated purpose of the paper was to promote discussion within the profession.

33. For the Fourth PanAmerican Conference on Soil Mechanics and Foundation Engineering, de Mello[9] wrote a state-of-the-art paper on the SPT. He stated that the best use of the SPT lay in determining in situ undrained strength parameters of the soil. De Mello believed that relative density estimations should be made from correlations with the angle of internal friction, ϕ , and not from a direct correlation with overburden stress and penetration resistance. This approach would require relating the SPT N-value to overburden pressure and the angle of internal friction. By statistical regression analysis he derived the following empirical relationship:

$$N = 4.0 + 0.015 \frac{2.4}{\tan \phi} \tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2}\right) e^{\pi \tan \phi} - 1$$

$$+ \sigma_v \tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2}\right) e^{\pi \tan \phi} \pm 8.7$$

According to de Mello, the above relationship, $N = f(\phi, \sigma_v)$, was sound for a variety of sands; however, $\phi = f(D_R)$ was not universal for all sands. If one accepts the premise that penetration resistance is a function of ϕ rather than D_R , then Gibbs and Holtz's[6] and Bazaraa's[7] correlations would be valid for sands with the same $\phi = f(D_R)$

relationship as the sands they incorporated in their respective studies.

34. The effect of overconsolidation, de Mello observed, was to create high residual horizontal stresses which could affect the penetration resistance. Since there were insufficient data to define the overconsolidation effect, de Mello suggested the effect on ϕ should be considered negligible for drained strength conditions, but could be significant for undrained strength conditions. In the area of future research, de Mello recommended utilizing more than one spoon, thereby enabling a sufficient number of simultaneous equations for computation of the separate contributing parameters.

35. De Mello suggested that the SPT could provide quantitative information for design at the price of conservatism. The test was valuable to those who realized its limitations and recognized circumstances which dictated the need to use information from other tests.

36. In 1971 Langfelder and Johnston[19] reported field experience with the settlement of two waste treatment tanks. The settlement was checked for 1 yr after construction in order to compare observations with predictions made from SPT's and confined compression tests. The settlement predicted using the SPT results and the settlement correlations was conservative. The confined compression test results were also conservative; however, they were much closer to the observed settlement than the SPT prediction. The conclusion was reached that considerable engineering judgment must be used in order to achieve economical foundation designs.

37. In 1971 Gibbs[20] published field data which reaffirmed that the earlier Bureau of Reclamation work gave a favorable correlation when compared to field conditions. Although not precise, the SPT proved an inexpensive alternative to other methods of subsurface exploration. Gibbs stated that the interpretation should be kept general, and recommended continuing correlations with field data as they become available. Gibbs considered research investigating the effects of small variations in gradation and moisture content unnecessary.

38. In 1971 Melzer[21] published findings which demonstrated that

in medium and coarse sands the number of blows measured for a given relative density is larger when the test is conducted above the groundwater level than when it is conducted in submerged sand. A chart was prepared which allowed one to correct the blow count value below the groundwater, N' , to the blow count value above the groundwater level, N . The plot was a straight line expressed by:

$$N = 5.27 + 1.05\,N' \pm 2.3$$

Melzer also found that the compactibility and mean grain diameter also influenced the results of the SPT. This relationship was expressed by the equation:

$$D_R = a_1 \log N + a_3$$

where

D_R = relative density

a_1 = constant related to compactibility

a_3 = constant related to mean grain diameter

N = blow count for SPT

39. The overburden term has been eliminated from this expression by assuming the tests to be conducted at the soil surface. Overburden can be included by determining a third constant, a_2 :

$$D_R = a_1 \log N + a_2\sigma_v + a_3$$

where

a_2 = constant

σ_v = overburden pressure

40. Melzer presented a table which listed values for constants a_1 and a_3 for four sands tested. No indication was given as to how to compute the overburden constant, a_2 .

41. Nowatzki,[22] 1971, presented a theoretical three-dimensional static analysis of the SPT using plasticity theory and the Coulomb

failure criterion. A numerical solution to the differential equations of plastic equilibrium for an ideal homogeneous dry sand was presented, to show the alteration of slip line field geometry and ultimate load effected by changes in variables. The variables considered were angle of internal friction, cohesion, friction angle between the cutting edge of the penetrometer and the side walls, penetrometer sidewall stress distribution, depth of overburden, and surcharge. He found the most important variables to be (a) loading distribution along the penetrometer sidewall, (b) angle of internal friction, and (c) consideration of the friction angles between the cutting edge of the penetrometer and the sidewalls of the penetrometer and the soil.

42. Nowatzki stated that many of the empirically recognized factors which influence the SPT were functions of one or more of the significant variables as shown by his theoretical solution. He believed that empirical correlations do not account for the important SPT variables; therefore, they can only be considered approximate and their quantitative worth is questionable.

43. In the discussions of de Mello's state-of-the-art paper, Peck[23] points out that the Terzaghi and Peck design curves correlate penetration resistance and allowable soil pressure for foundation design. Peck commented that while the SPT is crude, the poor correlation between it and relative density is a result of defects in the relative density concept, not the SPT.

44. Melzer[24] commented that for a correlation between penetration resistance and angle of internal friction, the normal stress acting in the rupture zone should be considered rather than the overburden pressure. The normal stress, however, is impossible to determine in the field. Therefore, a correlation of penetration resistance with relative density has more practical value.

45. Adam[25] presented analytical results demonstrating that the length of drilling rod was relatively unimportant. Adam's conclusion was based on a wave equation analysis of the rod-sampler system for "A" rod lengths of 30, 60, and 120 ft. The results were presented in the form of a plot of relative penetration resistance versus blows per 6 in.

The greatest variation was approximately 4 blows per 6 in. Adam also investigated slackness at the rod joints and found that joint slackness did not alter the results significantly.

46. De Godoy[26] reported the SPT results obtained during the subsoil investigation of three sites where he employed three different rod sizes. The rod sizes used were: 1-in. rod, A-rod, and B-rod. The penetration resistance with depth for the three different rod types did not differ significantly. De Godoy concluded that the rod weight was relatively unimportant.

47. Schnabel[27] recommended a different procedure for seating the split spoon. He felt that seating the spoon with a few light taps, depending upon the driller's skill and experience, was preferable to the accepted method of driving the split spoon 6 in.

48. Schmertmann[28] conducted tests with a cone penetrometer in order to study isolated parameters which could influence the Cone Penetration Test (CPT). Based on energy considerations, he suggested a relationship between the CPT and SPT. From this relationship, he suggested that the low blow count often observed in soils without gravel for the first 6-in. interval perhaps does not reflect a seating of the spoon in loosened soil, but rather illustrates the fact that end bearing resistance is of minor importance and sidewall friction is very significant.

49. In the discussion to de Mello's state-of-the-art report, Janes[29] presented the results of SPT tests performed on a sand fill before and after densification. Janes concluded that if a positive relationship exists between SPT N-values and relative density, it varies between types and gradations of sand as well as with the proximity of other soils. He also stated that the Gibbs and Holtz[6] criteria overestimate the relative density near the surface, and should not be specified as the control measure for load-supporting sand fills.

50. Tavenas[30] feels relative density is a poor index to use in conjunction with the SPT N-values. He demonstrated that a given N-value has an associated standard deviation which, when applied to the Gibbs and Holtz[6] correlation curves, yields a bandwidth of relative density values rather than a single value. This factor, coupled with the

certainty that relative density can vary due to the inherent difficulties in establishing this index, led Tavenas to conclude that in situ relative density estimates cannot be reliably established from the SPT N-values.

51. In 1973 Serota and Lowther[31] conducted a comparison of the various techniques used to drive the split spoon sampler. These included: (a) slip rope and cathead with one, two, or more turns, (b) the Pilcon trip monkey, (c) Dando trip monkey, (d) hand-dropped, and (e) Pilcon winch. They found that the specification for an absolute free fall is not satisfied if more than one turn of the rope is made on the cathead. Their results corresponded very closely with the Gibbs and Holtz[6] results if two or more turns were used. A ratio of blow counts of 1:1.4 was found between one rap and two or more raps; this is in agreement with results published by Frydman.[32] The Pilcon trip monkey and the ASTM method using one turn on the cathead yielded identical results. The results obtained using the cathead and one turn of the slip rope were reproducible to within a standard deviation of 10 percent. However, this may have been a result of the test conditions, i.e., no borehole, dry compact sand.

52. McLean, Franklin, and Dahlstrand[33] performed a wave equation analysis of the SPT apparatus to determine the influence of some mechanical variables on the SPT. They modeled the soil resistance using the results presented by Schmertmann,[28] and others, for an insensitive cohesive soil. Two hammer types, pin-guided and center hole, were investigated. The results of their study indicated that deviations from the ASTM 30-in. drop height can significantly affect the N-value, particularly as the penetration resistance of the soil becomes increasingly greater. A-rod and N-rod results were compared; it was observed from the calculations that the N-rod yielded a slightly higher blow count than the A-rod, approximately 1 blow per 6 in. for 18-in. penetration. Length of rod appeared to be an important consideration in evaluating SPT results. A comparison was made between 10-, 50-, 100-, and 200-ft lengths. A maximum variation of 6 blows per 6 in. was observed between the 10- and 50-ft depths.

53. Schmertmann[34] surveyed the profession and found diverse opinions with regard to the use of the SPT. He reported that the profession generally regards the test as crude, useful only for the purpose of preliminary assessment of site conditions, and unacceptable as a design or control criterion. For those partial to the test he stated, "We are learning more about the dynamics of the test and about the various factors that influence its results. If this trend continues we may soon be in a position to quantify the results from the test on a theoretical basis as well as the current exclusively empirical basis."

54. In summary, it is observed that the SPT has, in a quantitative sense, not advanced much beyond the original effort of driving an open-end pipe into the ground; however, it has found international acceptance by many in the profession and remains one of the most efficient and inexpensive procedures for site investigations.

55. In the following pages of this report, the results of a full-scale laboratory SPT program will be presented. The test program was conceived to contribute to the understanding of the accuracy of the SPT when used to determine in situ relative density. Additional information related to the basic nature of the SPT and its variables resulted from the performance of these tests, and is reported herein.

PART III: TEST FACILITY

Introduction

56. The testing facility used consists of five major components: the stacked-ring soil container, the foundation, an overburden loading system, the drilling equipment, and the sampling equipment.

Stacked-Ring Soil Container

57. The stacked-ring soil container, Figure 1, consists of alternating layers of steel rings with 1-in.-square cross section and nominally 3/16-in.-thick rubber spacer rings. The internal diameter of the rings is 4 ft. The steel ring is grooved to receive a mating key molded on the rubber spacer ring, Figure 2. The stacked-ring soil container was developed from a study conducted by Dr. M. Juul Hvorslev[35] and is similar in concept to a smaller diameter device used at Stanford Research Institute.[36]

58. The stacked-ring soil container was developed to minimize the effect of wall friction common to solid wall containers, where wall friction causes an undesirable reduction in soil stress with increasing container depth. Hadala[37] found that the soil stresses due to dead weight in a solid wall container could be reduced by as much as 50 percent at a depth equal to the specimen diameter. Additionally, he found that soil stresses due to applied loads can be reduced by one-third at a depth equal to one diameter.

59. The effectiveness of the stacked-ring soil container was observed during the course of this program. Micrometer measurements of the vertical deformation of the rubber spacer rings were made during test 4, with the specimen loaded to 80 psi. Individual rubber spacer rings typically compressed 0.0035 in. In a subsequent test conducted on an empty 2-ft-high section of stacked rings, it was determined that an average deformation of 0.0035 in. per rubber spacer ring corresponds to a vertical load of 750 lb on the container. Thus, the maximum load

Figure 1. Stacked-ring soil container

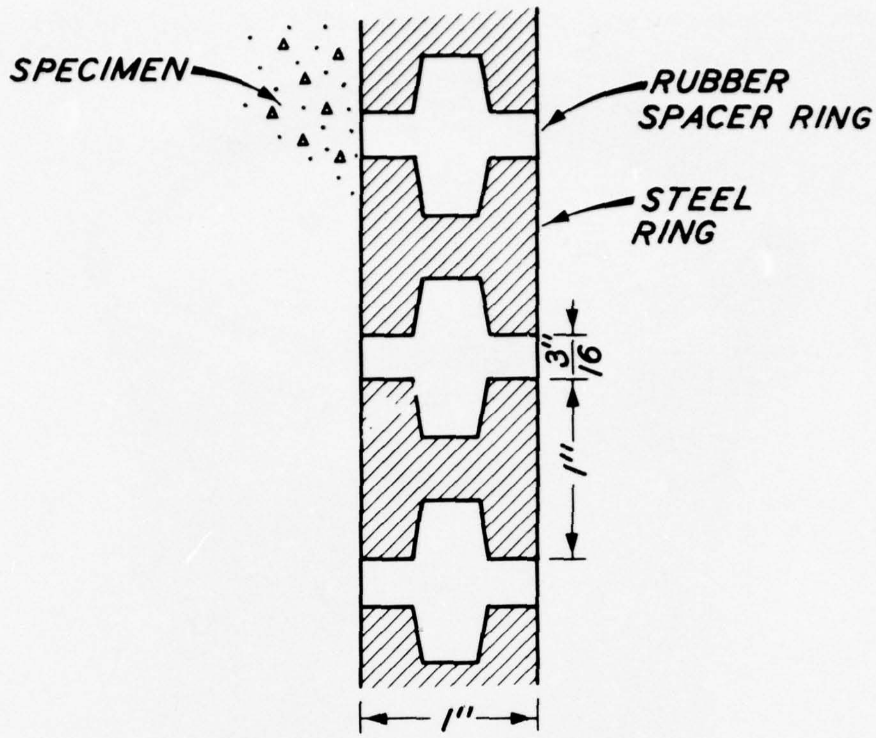

Figure 2. Cross-section view of typical steel
rings and rubber spacer rings

transmitted to the soil container via soil friction in test 4 is assumed to be 750 lb or 0.5 percent of the total applied vertical force of 144,765 lb. It is thereby assumed that the remaining 99.5 percent of the load was transmitted to the soil specimen.

60. While the rubber spacers allow the desired vertical flexibility, the steel rings provide the necessary lateral restraint. Calculations based on typical sand specimens indicate that radial deformation should not exceed 0.024 percent for a maximum vertical applied load of 300 psi. Hence, the stacked-ring soil container provides a suitable medium for representing field conditions.[8]

Foundation

61. The massive monolithic reinforced concrete foundation was

designed to react the vertical forces developed in dynamically loading 4-ft-diam specimens to 300 psi. Consequently, static loadings to 300 psi are easily reacted.

62. Figure 3 is a cross-sectional view of the test apparatus. Two 4-ft-high concrete pedestals serve to react the action of the overburden loader system (to be discussed subsequently). The top of the foundation monolith is at floor level, and a specimen preparation well extends to a depth of 6 ft into the foundation. A 4-ft-diameter hole extends from the bottom of the specimen preparation well 6-1/2 ft through the foundation to a sand blanket overlying the natural substratum. From the base of the foundation to approximately 4 ft above the base, this hole was backfilled with highly compacted Reid Bedford Model sand. At this location an impermeable barrier was constructed to prevent downward seepage to the foundation materials. Above the impermeable barrier layers of graded filter material were placed to provide a capability for specimen submergence from the bottom up. A perforated water hose was threaded through the cable way to the rock filter. An auxiliary water hose was provided to fill the specimen preparation well; thus, the water levels in the specimen preparation well and the specimen could be maintained approximately equal during the submergence phase.

Overburden Loader System

63. The application of overburden pressure, simulating testing at desired depths beneath the ground surface, was accomplished with an overburden loader, Figure 4. The overburden loader consists of a ram and reaction beam assembly, a cylindrical steel loading head, and a fiberglass-reinforced rubber water-filled pressure equalization bag. Vertical load is applied to the specimen by means of three hydraulic rams. The reaction beam assembly, anchored to the two concrete pedestals shown, reacts the vertical force developed by the rams. The water bag is placed between the loading head and the specimen surface and serves to uniformly distribute the vertical load applied to the specimen. The rams are individually driven by three manually operated

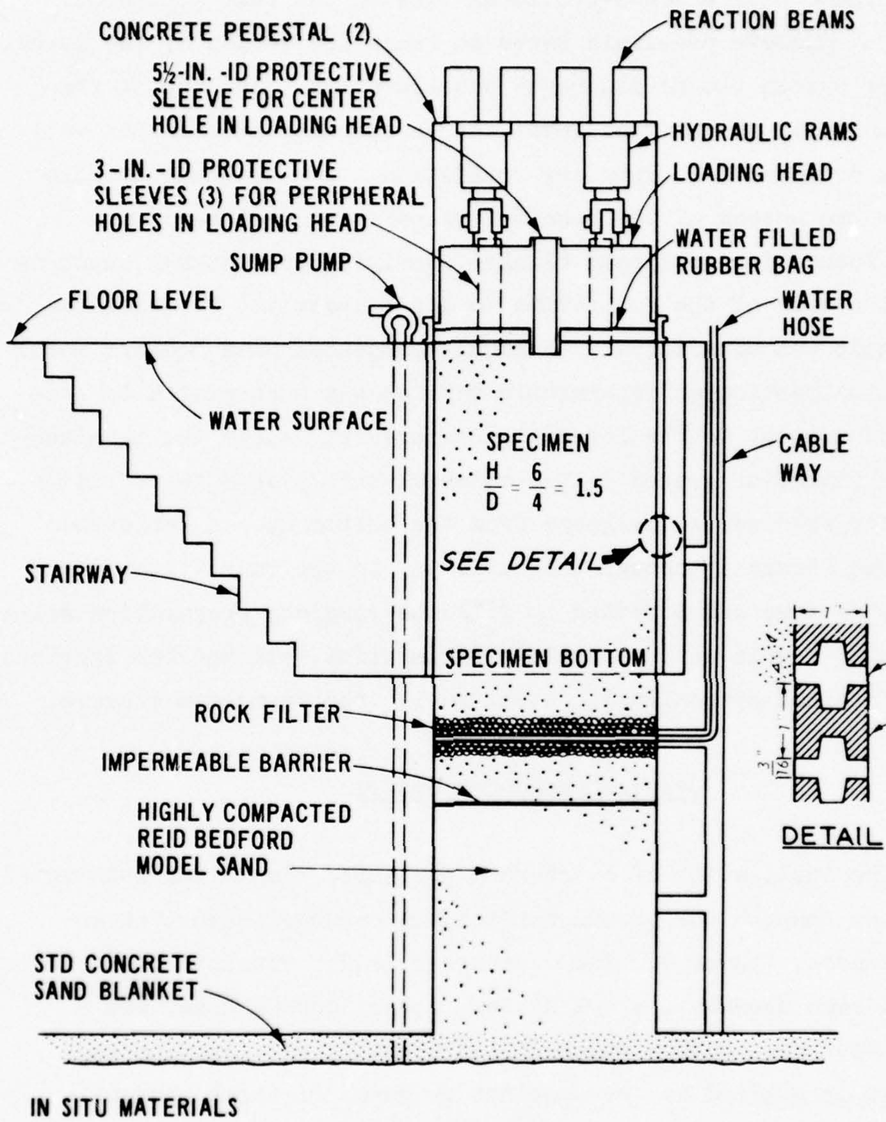

Figure 3. Sectional view of test apparatus

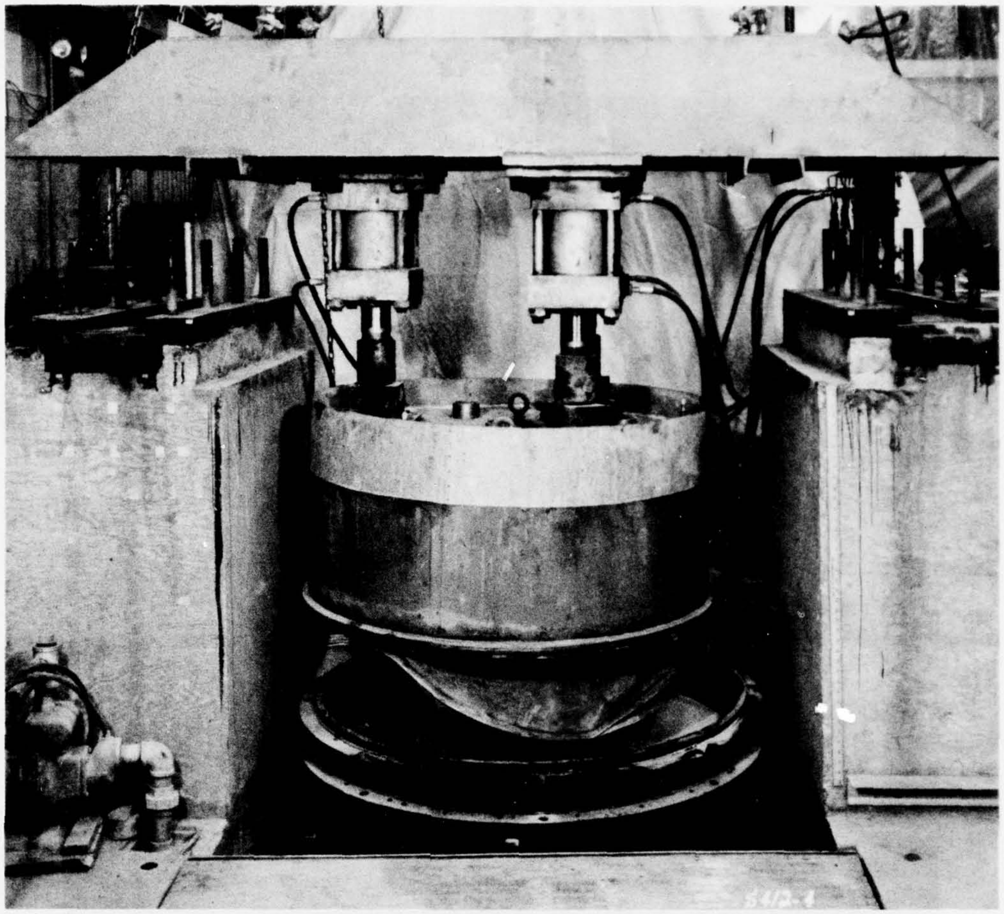

Figure 4. Overburden loader system

hydraulic pumps which are mounted on a portable console containing the hydraulic fluid reservoir, Figure 5. Hydraulic pressure delivered to each ram is monitored with a console-mounted Bourdon gage.

64. The loading head is outfitted with four sleeves which extend through the head and the water bag and penetrate 2 in. into the soil specimen surface, Figure 6. They serve to guide the samplers and protect the water bag. The fiberglass-reinforced rubber water bag is filled by means of two tubes which extend upward through holes provided in the loading head. Bag pressure, which is equal to the applied vertical stress, is monitored by a calibrated Bourdon gage connected to the filler tube. The periphery of the water bag is confined by a 6-in.-high

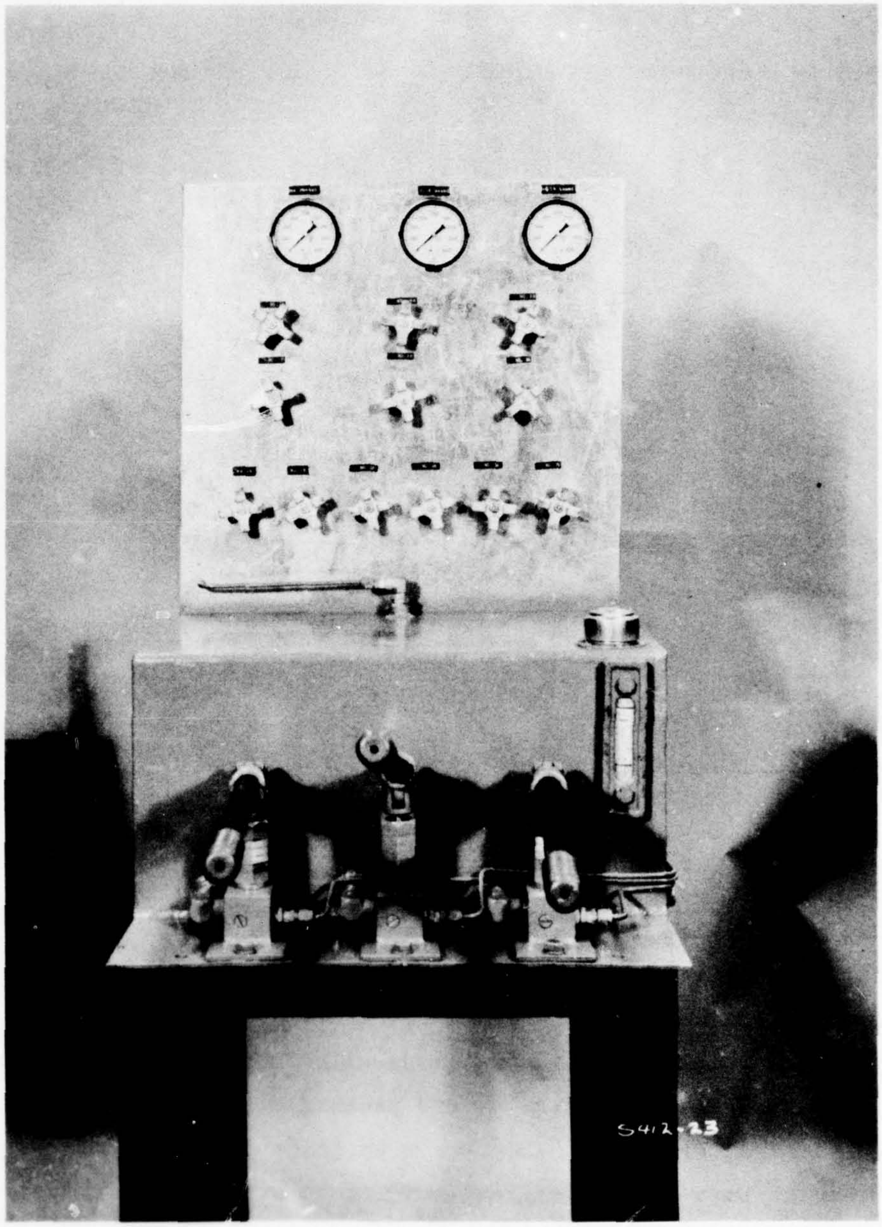

Figure 5. Manually operated portable console used to hydraulically extend rams on overburden loader

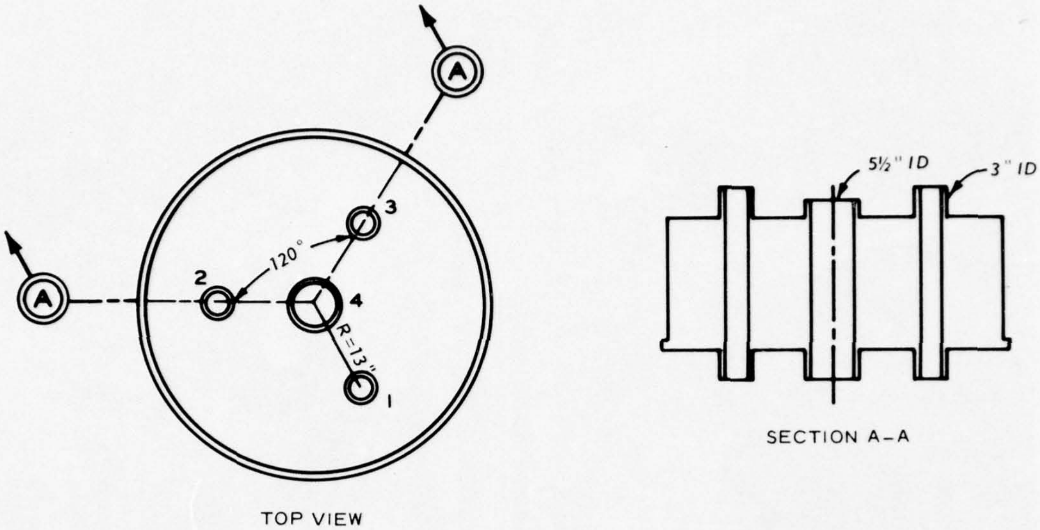

Figure 6. Location of sleeves in loading head

machined steel collar which rests on the top steel ring, Figure 4.

Drilling Equipment

65. Sampling and performance of the SPT were accomplished using a commercially available skid-mounted Acker Toredo Mark II soil sampling drill, Figure 7. Low overhead clearance prohibited the use of a derrick, so lifting tackle for the drill rods was secured to rafters in the ceiling. To accomplish the drilling and sampling the rig is elevated on a platform, level with the top of the loader support pedestals. All testing was done with commercially available drilling mud supplied from a reservoir atop the loading head, and circulated by a portable mud pump. N-weight drill rods were used throughout the testing program. The maximum length of drill rod did not exceed 11 ft; the minimum length was 5 ft. The split spoon sampler was driven by a hydraulically operated 140-lb hammer contained in a perforated cylinder, Figure 8. The hammer, designed by the Vicksburg District, Corps of Engineers, is mechanically lifted to a 30-in. drop height by two lugs positioned on a continuous chain. The chain is driven by a hydraulic motor connected to the hydraulic system of the drill rig.

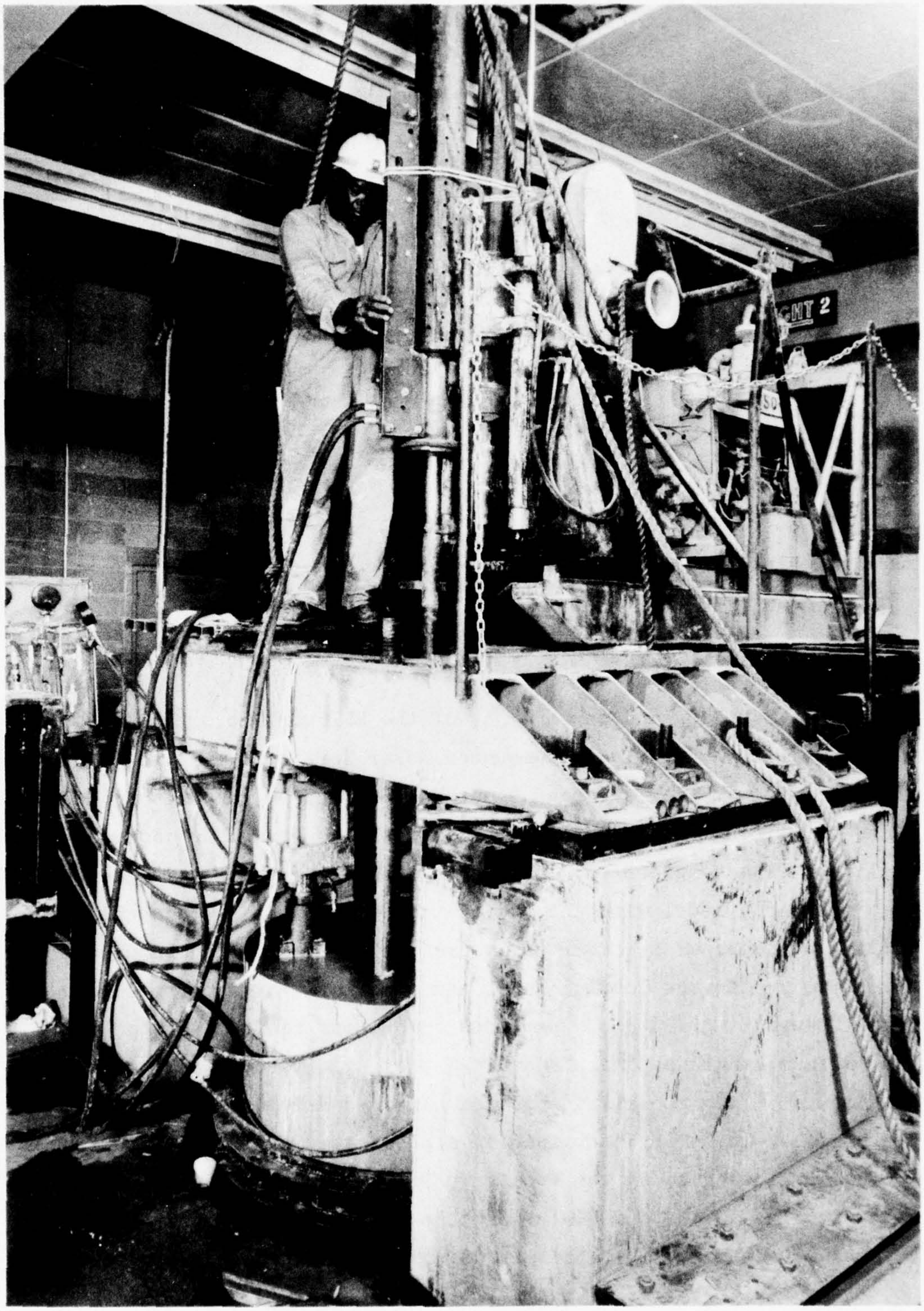

Figure 7. Test facility in operation

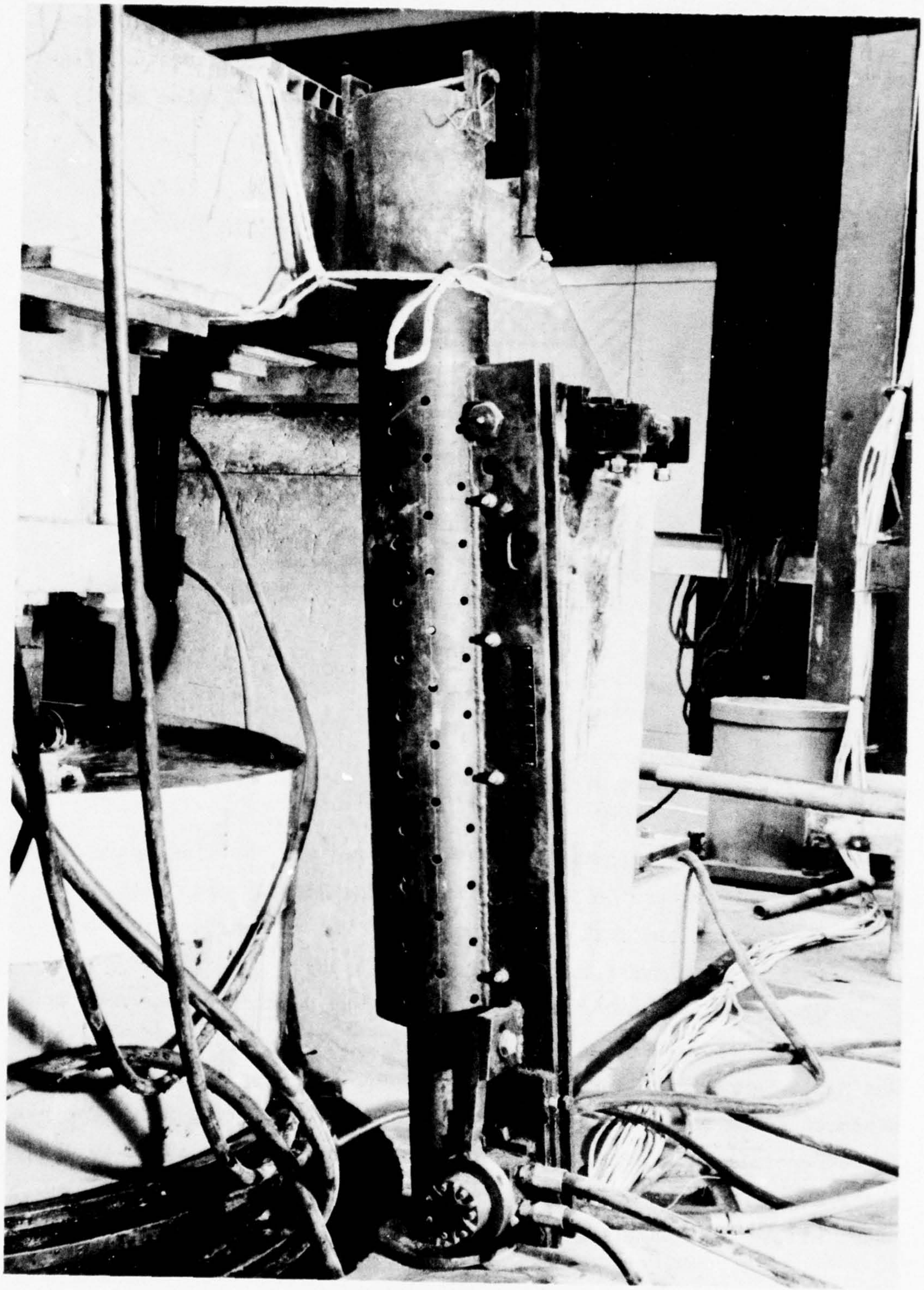

Figure 8. Hydraulically driven 140-lb trip hammer

66. Driving the split spoon sampler with this hammer is accomplished by inserting the drill stem into the cylindrical housing, Figure 9. The hammer free-falls 30 in., striking the drill stem only. A

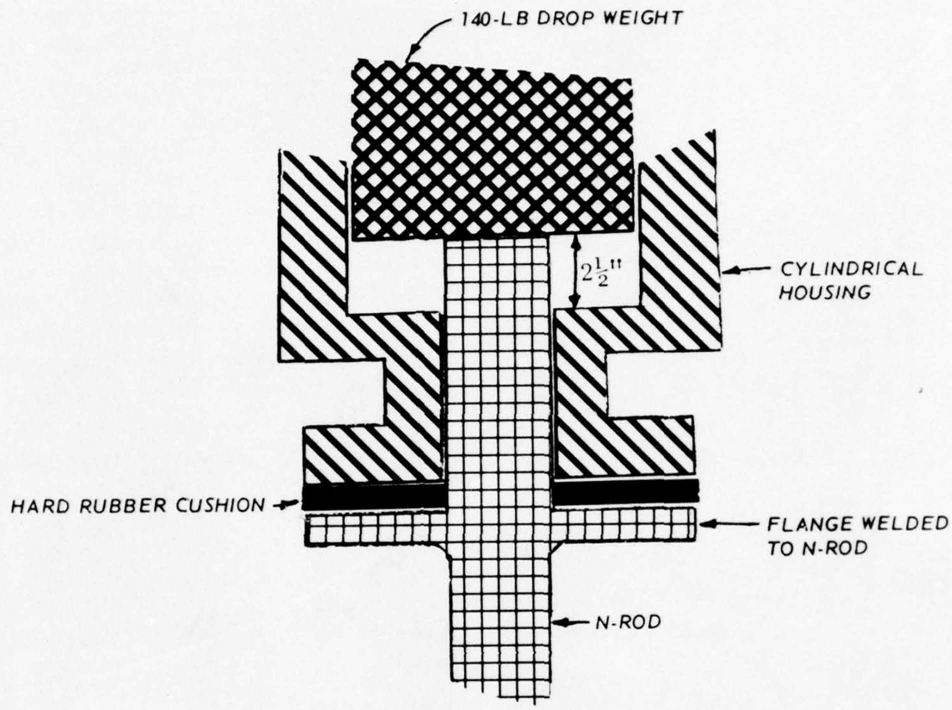

Figure 9. Cross-sectional view of the split spoon drive mechanism

1-in. steel flange supports the housing during the sampling operation, and a hard rubber cushion is used between the housing and drill stem flange to cushion the fall of the housing. The rate of driving was approximately 15 blows per minute for this study.

67. The split spoon sampler used in the conduct of the test conforms to the specifications outlined in ASTM D1586-67, Penetration Test and Split-Barrel Sampling of Soils,[38] Figure 10. The borehole was advanced using the WES-modified fishtail bit and drilling mud. The bit is commercially available; however, special baffles were added to direct the flow of drilling mud in an upward direction, thus reducing disturbance at the next sampling level.[3]

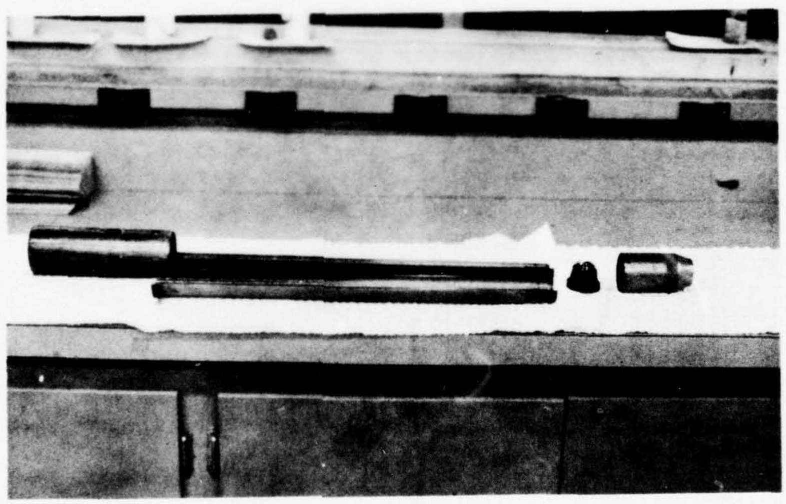

Figure 10. Split barrel sampler

PART IV: TEST PROGRAM

General

68. The SPT's reported herein consisted of testing 26 specimens, 4 ft in diameter by 6 ft high, built to varying relative densities and tested under a range of overburden pressures. A test specimen was constructed by one of several placement techniques which will be discussed subsequently.

69. Two fine uniform sands (SP) were used during this phase of the program. The first sand tested was Reid Bedford Model sand, a locally procured material with a coefficient of uniformity of 1.6. Figure 11 depicts the grain size distribution of the Reid Bedford Model sand. The

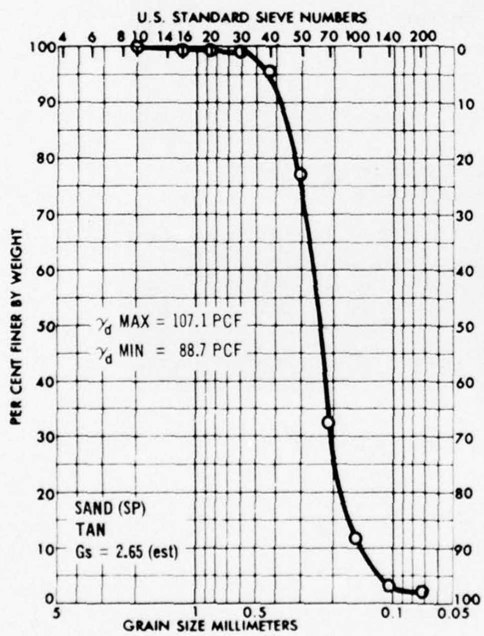

Figure 11. Reid Bedford Model sand grain size distribution curve

D_{50} is approximately 0.25 mm, and the grain shape is subangular to subrounded. A petrographic analysis of the Reid Bedford Model sand is included as Appendix A. The second sand tested was Ottawa sand, which has a uniformity coefficient of 1.5 and a D_{50} of 0.21 mm, Figure 12. A petrographic analysis of Ottawa sand is included as Appendix B.

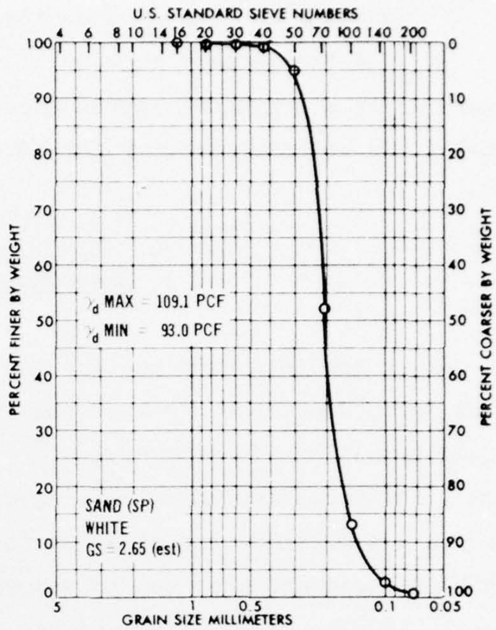

Figure 12. Ottawa sand grain size distribution curve

Relative Density

70. The maximum and minimum dry densities of the respective sands were determined by the procedures contained in Engineer Manual 1110-2-1906, Laboratory Soils Testing.[39]

71. Maximum density is achieved by vibrating the soil specimen on a vibratory table for 8 min, at the maximum amplitude of the table. The minimum density is found by carefully pouring air-dry sand through a 1-in.-diam spout for a free fall of approximately 1 in. Both tests were performed dry.

72. Once the maximum and minimum dry densities of the soil are known the relative density can be determined by the expression:

$$D_R = \frac{\gamma_{max}(\gamma - \gamma_{min})}{\gamma(\gamma_{max} - \gamma_{min})} \times 100$$

where

D_R = relative density expressed as a percent

γ_{max} = the densest packing of the soil

γ = the density of the material in the specimen

γ_{min} = the loosest packing of the soil

Figure 13 is a graphical representation of the relationship between dry density and relative density for Reid Bedford Model sand and Ottawa sand.

Box Density Device

73. Specimen construction was accomplished by placing 4- to 6-in. lifts, with density control of the individual lifts achieved using the WES-developed box density device.[40] The device is a 4- by 12-in. metal form 3 in. deep, including cutting edges, Figure 14. A box-shaped scoop and a scraper-type cleanout tool, corresponding to the desired depth of cleanout, are used to remove the soil from within the box. The form is 16-gage sheet metal and has a 3/4-in.-thick rectangular plate attached to the upper edge of the form to provide a lip. This plate rests on the sand surface when the box is pressed into the sand to a depth of 2-1/2 in.

74. The accuracy of the box density device was observed to be within ± 0.3 pcf for the range of dry densities involved in this study. The deviation from the actual density appeared to be random; hence, no effort was made to correct the measured density.

Correction for Overburden Pressure

75. Overburden pressure was applied to every specimen according to a prescribed test schedule. The usual pressures were 10, 40, or 80 psi. Some specimens were tested at only one pressure, while others were stage tested at two or more pressures. The application of the overburden pressure caused consolidation within the specimen, densification being significant for loosely prepared specimens and minimal at the higher densities. A density correction for overburden pressure was derived from the results of one-dimensional consolidation tests performed on submerged 3-in.-diam specimens at the same testing pressures

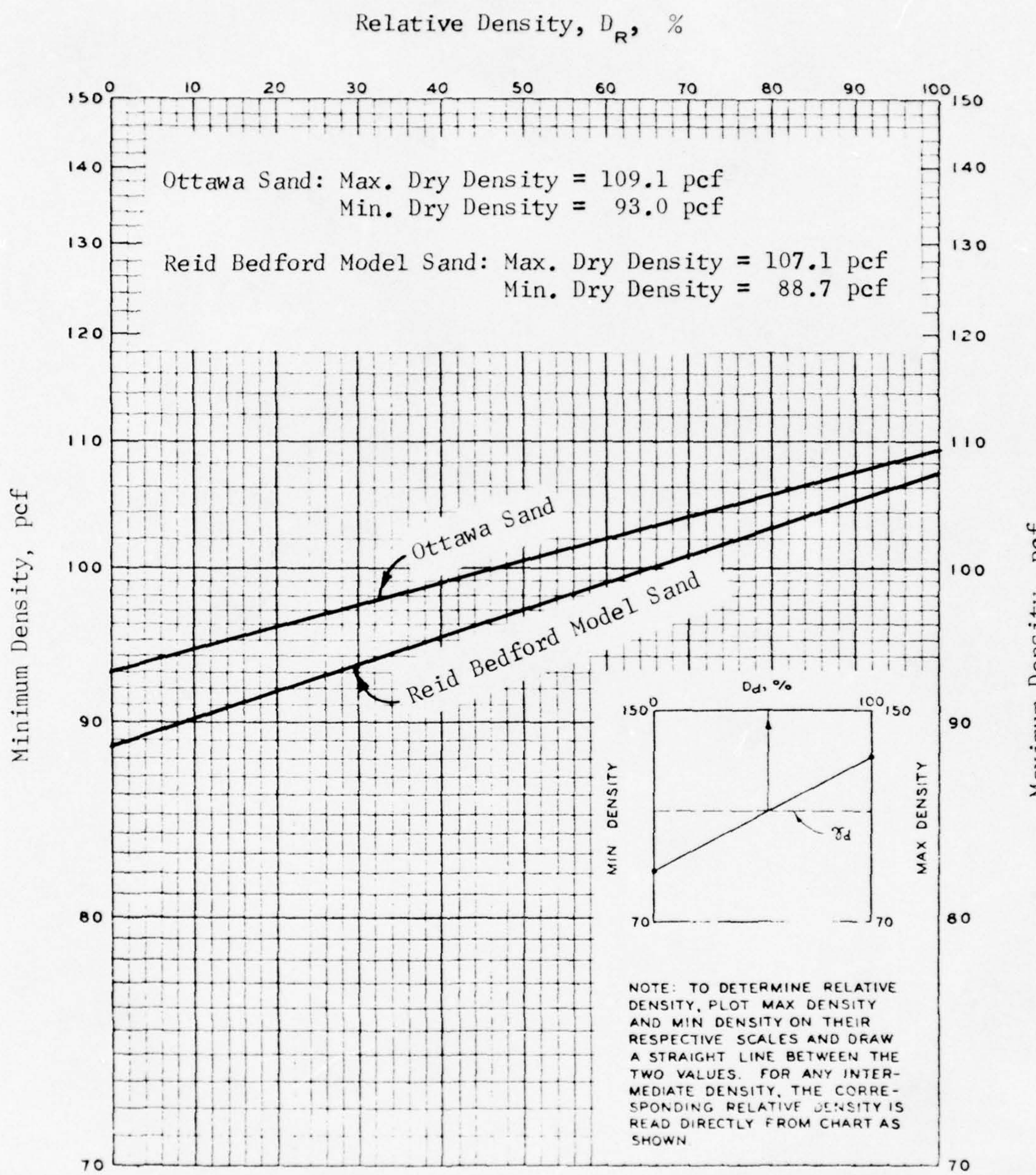

Figure 13. Graphical determination of relative density, Reid Bedford Model sand and Ottawa sand

Figure 14. WES-developed box density device

used in the full-scale laboratory test program. The one-dimensional consolidation test was assumed to be analogous to the stacked-ring soil container.

76. Three consolidation tests were performed on submerged specimens of Reid Bedford Model sand at 20, 50, and 70 percent relative densities. The results of these tests at 10-, 40-, and 80-psi overburden pressures are presented in Figures 15, 16, and 17. Figure 18 is a semilog plot derived from Figures 15, 16, and 17, depicting the increase in dry density caused by an increase in overburden pressure. Since only three densities were tested, linear interpolation was used to obtain the family of curves displayed.

77. These data were subsequently used to obtain an arithmetic dry density versus dry density increase plot, Figure 19. The correction factor for a given overburden pressure was added to the average placed density between elevation 2.0 and 4.5 ft. This region corresponds to the second and third drives with the split spoon sampler, and is considered to have been least affected by the specimen boundary conditions.

78. A single one-dimensional consolidation test was performed on a submerged Ottawa sand specimen at 55 percent relative density, Figure 20. This was considered sufficient since both Ottawa sand specimens tested were built to a relative density of 55-60 percent. Figure 21, derived from Figure 20, shows the increase in dry density attributed to increases in overburden pressure. A correction chart was not developed for Ottawa sand; the corrections were taken directly from the results of the odometer test, i.e., from Figure 21, 0.5 pcf in the 0- to 10-psi range, and 0.5 pcf in the 10- to 40-psi range. Density corrections were added to the average placed densities determined by the box density device in the middle third of the specimen.

Sand Placement

79. The specimens were constructed incrementally (i.e., in lifts) by various raining procedures. The lift thickness ranged between 4 and 6 in. depending on the raining technique employed. The dry density

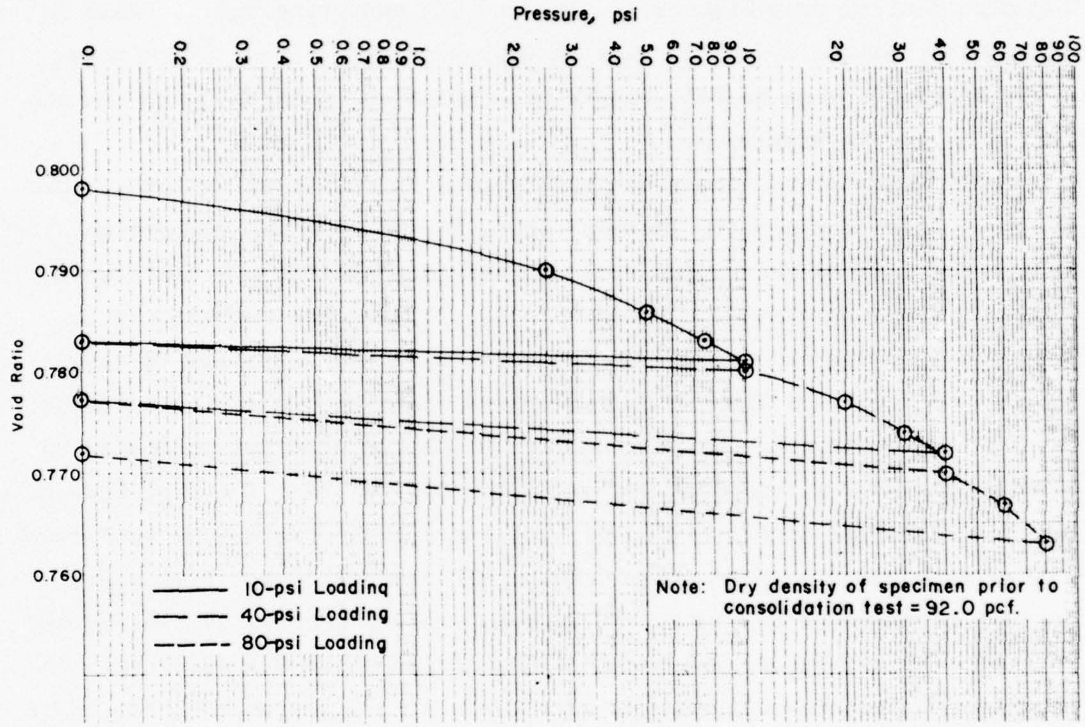

Figure 15. Results of consolidation test on Reid Bedford Model sand; γ_d = 92 pcf

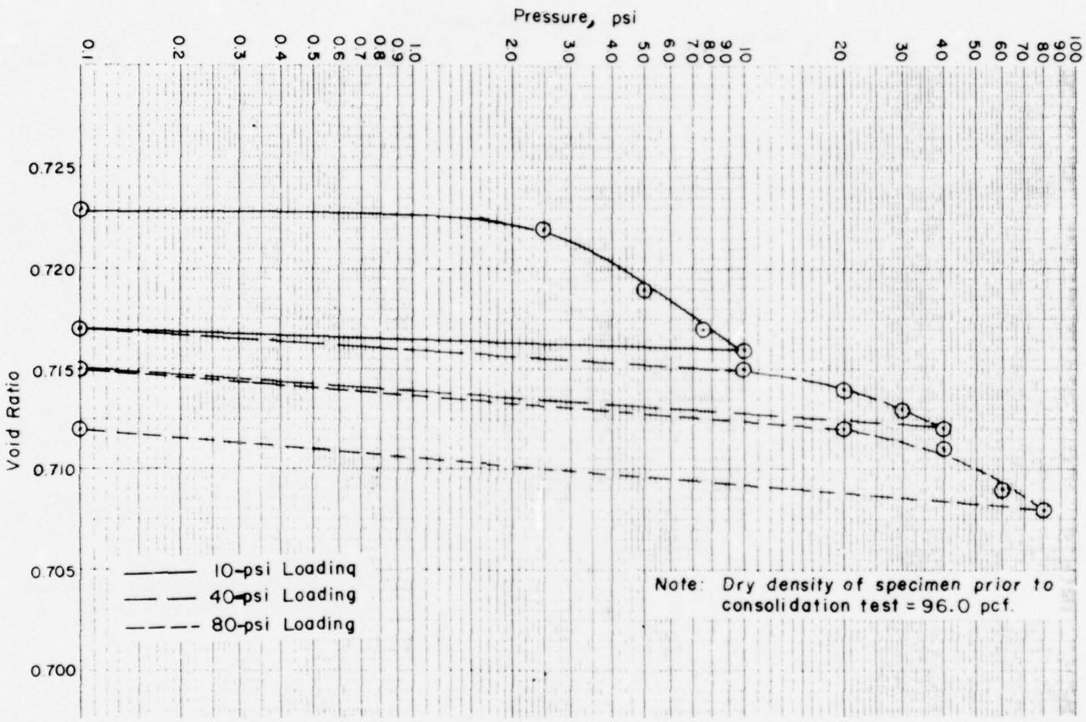

Figure 16. Results of consolidation test on Reid Bedford Model sand; γ_d = 96 pcf

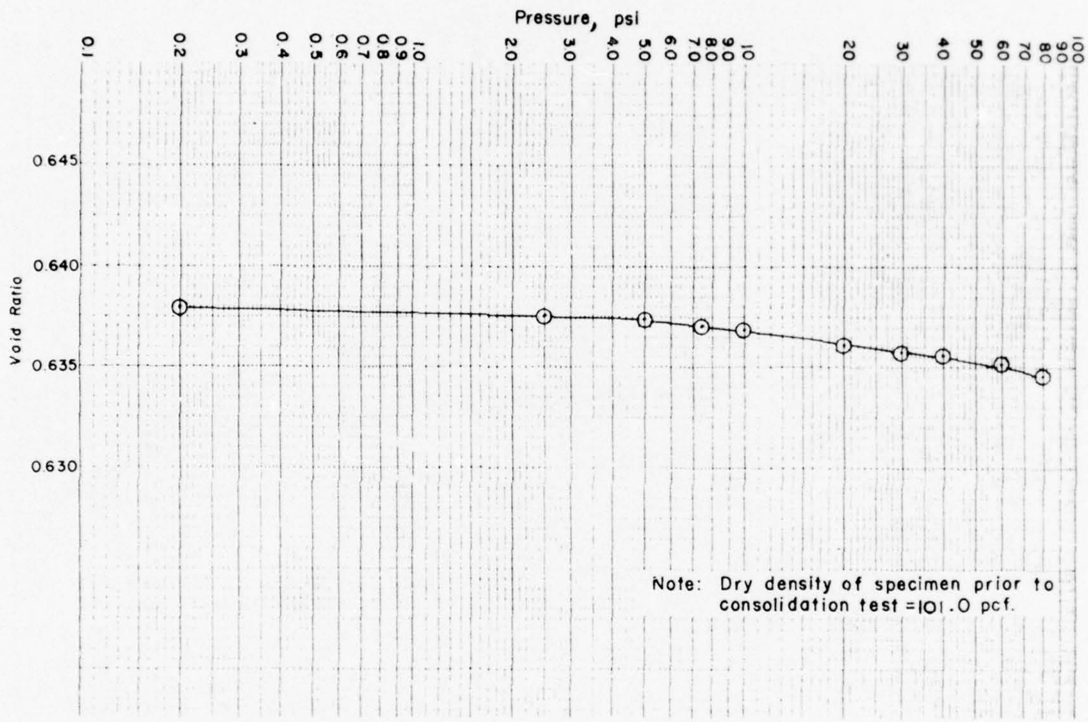

Figure 17. Results of consolidation test on Reid Bedford Model sand; γ_d = 101 pcf

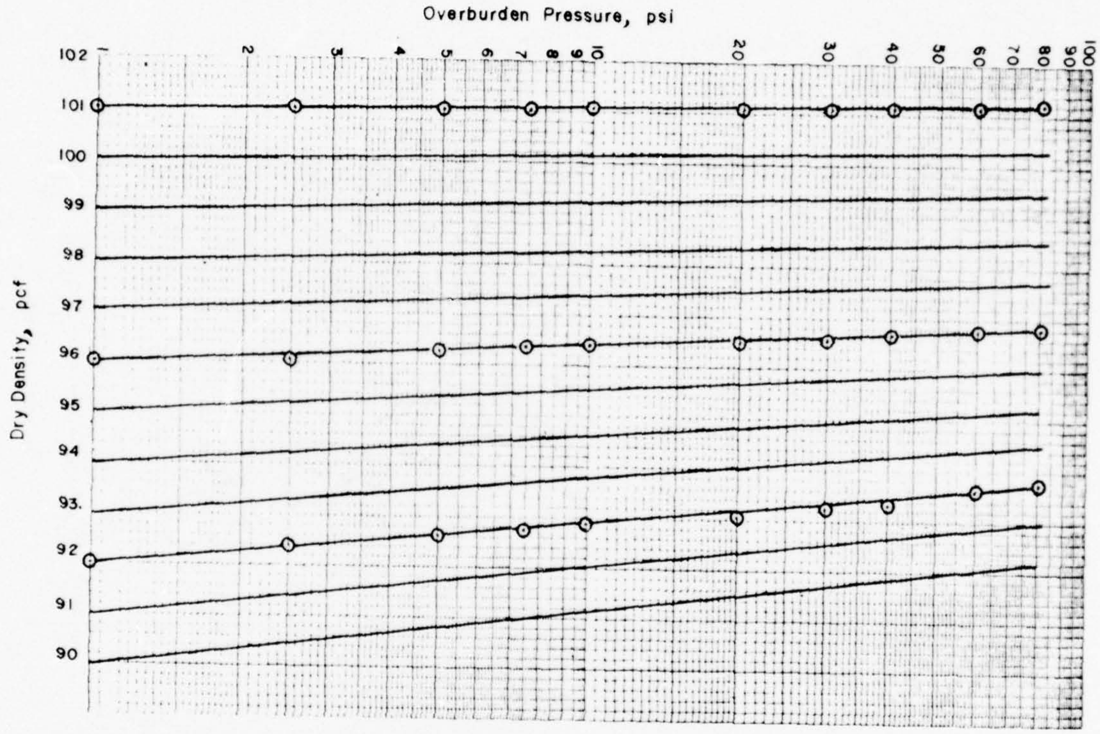

Figure 18. Overburden pressure versus dry density derived from consolidation tests on Reid Bedford Model sand

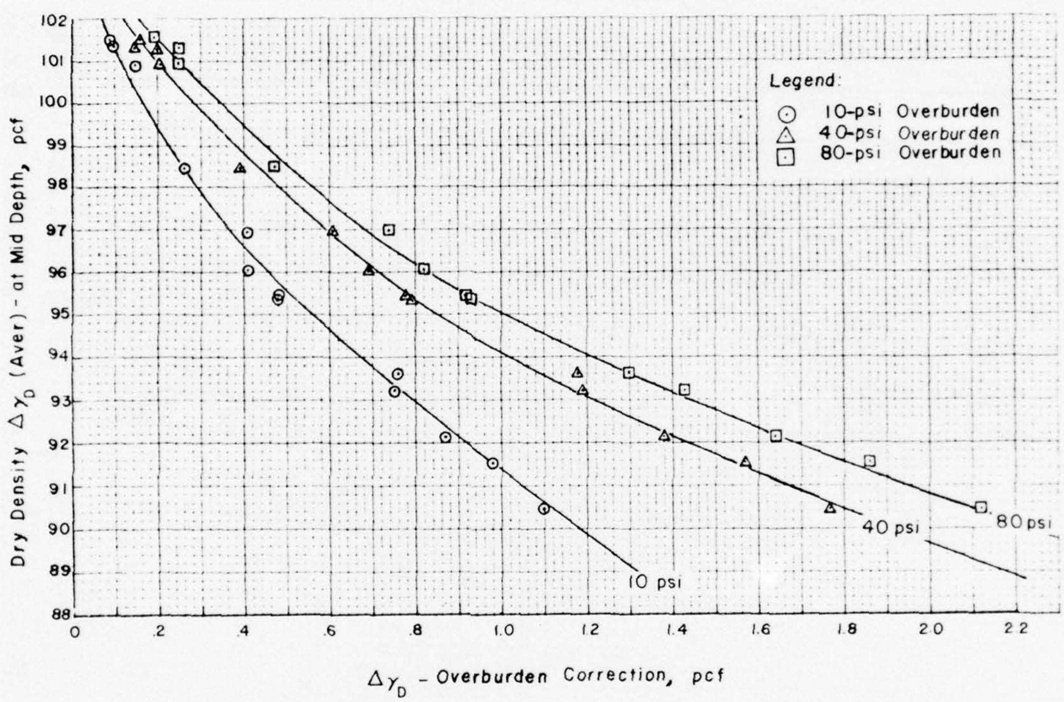

Figure 19. Density increase of Reid Bedford Model sand for overburden pressures of 10, 40, and 80 psi

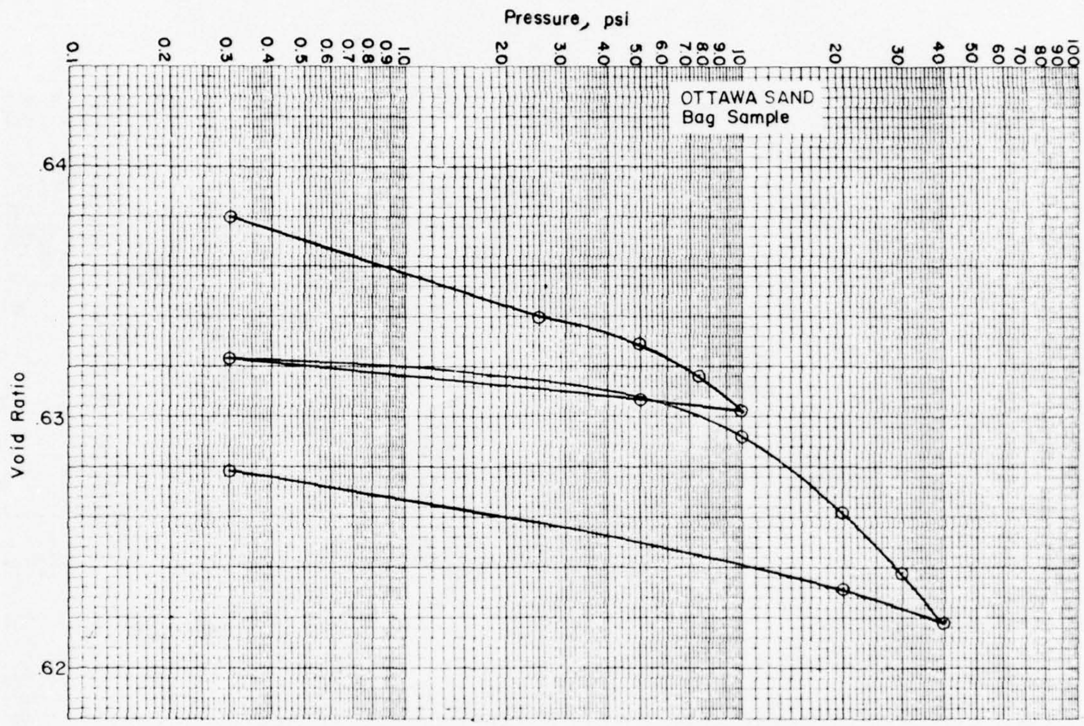

Figure 20. Consolidation test results on Ottawa sand

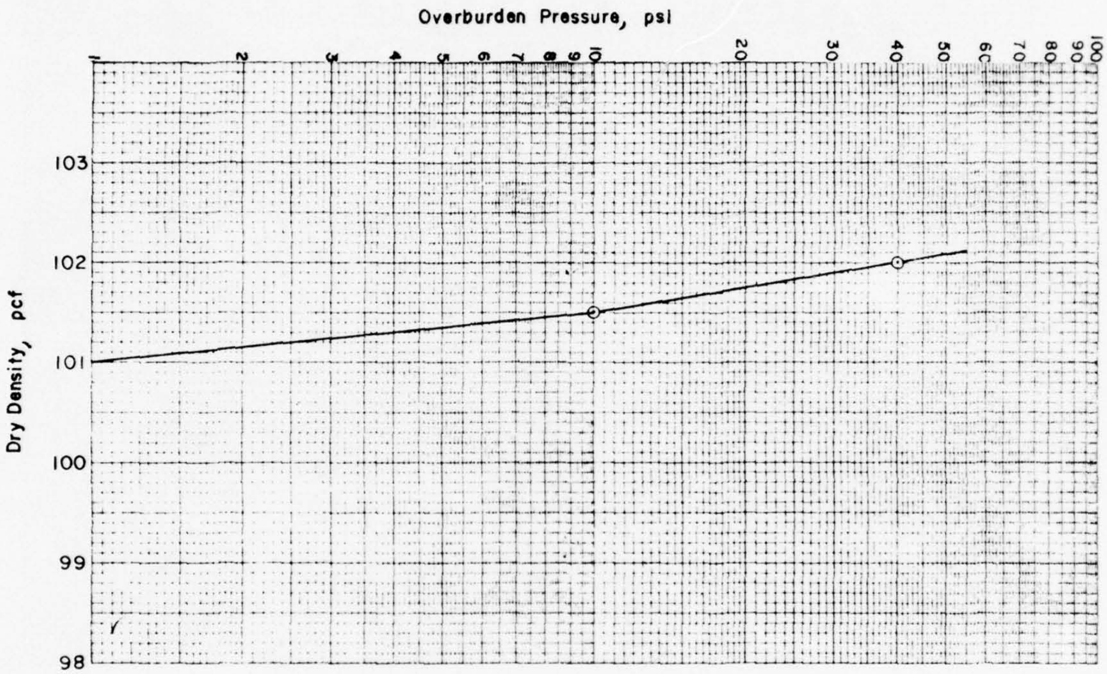

Figure 21. Dry density versus overburden pressure derived from consolidation test on Ottawa sand

determinations for test specimens 1-3, 9, 10, 14, and 15 were overall bulk densities based on a knowledge of the total weight of sand placed and the initial total volume of the soil specimen. Density control of the other test specimens was achieved using the box density device.

80. During the course of testing, three types of rainers were utilized: (a) a rotating rainer, (b) a single-hose rainer, and (c) a circular perforated plate rainer. The rotating rainer was the first developed, and enabled a change in lift density by varying the height of drop or intensity of raining. The rainer consisted of a reservoir with 28 flexible hoses, Figure 22. The sand flowed from the hoses normal to a diffuser plate, which intercepted the flow of sand and caused the sand to be evenly distributed on the specimen surface. The desired surface profile was generated by adjusting the tube orientations in relation to the diffuser plate. This equipment efficiently deposited 6-in. lifts.

81. The rotating rainer was manually rotated at approximately three revolutions per minute. An experienced technician could easily obtain repeatable lifts of uniform density, if the densities were checked at a single location; however, when several measurements were made along the radius of a particular lift, variations in the density were observed. Figure 23 is a plot of dry density versus radial distance for several lifts placed with the rotating rainer. From this it can be observed that density determinations made at the center of the lift are within an acceptable range (± 0.75 pcf). Densities taken at other points along the radius of each lift do not agree as favorably with the center-line densities, or with the corresponding densities of the other lifts. The maximum variation was approximately 6 pcf, which was considered unacceptable.

82. Several of the test specimens constructed with the rotating rainer were tamped with a 1-ft-square plate welded to a 4-ft-long steel handle in order to achieve higher densities. Tamping was accomplished by striking the sand surface along an imaginary grid pattern. This procedure resulted in a high-density lift, which was approximately 1.0 pcf more dense in the center than along the outer radius.

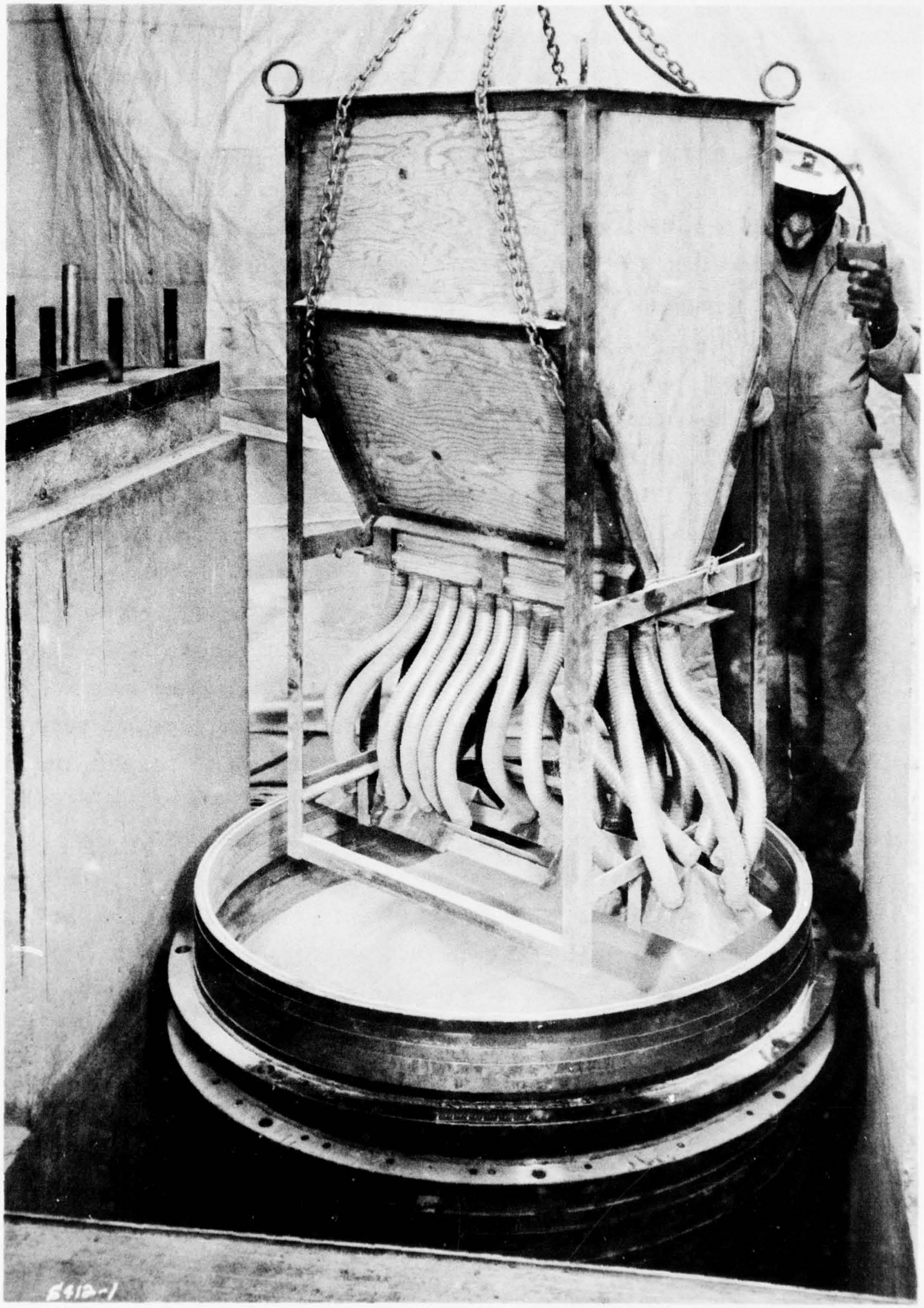

Figure 22. Rotating rainer

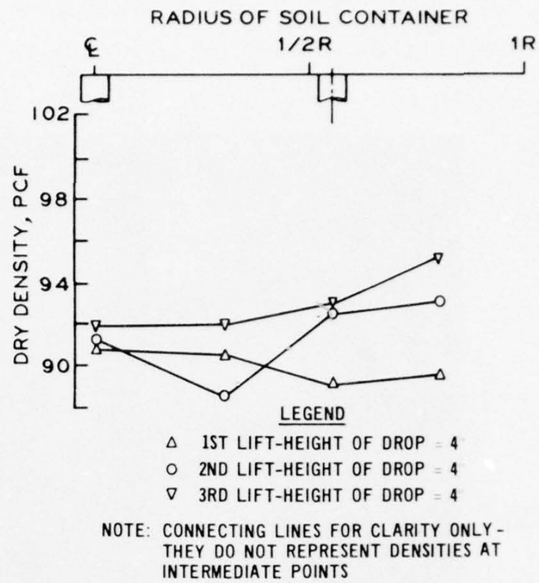

Figure 23. Dry density variation in lifts constructed with rotating rainer

83. During the course of the program it appeared desirable to rain sand into water using the rotating rainer. This technique was presumed to be advantageous from the standpoint of obtaining a greater degree of saturation. Density determinations were based on the bulk weight of sand placed and the total volume of the soil specimen. A specimen rained by this technique, without any further compaction effort, was calculated to have a relative density of approximately 20 percent. Higher densities desired in the test program were achieved by rodding each lift on an imaginary grid pattern with an open-end 2-in.-ID pipe. Four test specimens were constructed by raining into water; the results of the SPT's on these specimens are covered in a subsequent section.

84. Further efforts to improve density control resulted in the development of the second rainer shown in Figure 24. This rainer consists of a reservoir which feeds a single hose. At the exit of the hose, a series of three 1/4-in. screens were placed to break the fall of the sand.

85. Density was varied by changing the height of fall from the screens to the sand surface. Sand was placed in 6-in. lifts by directing the material flow with the hose. Uncontrolled flexing of the hose

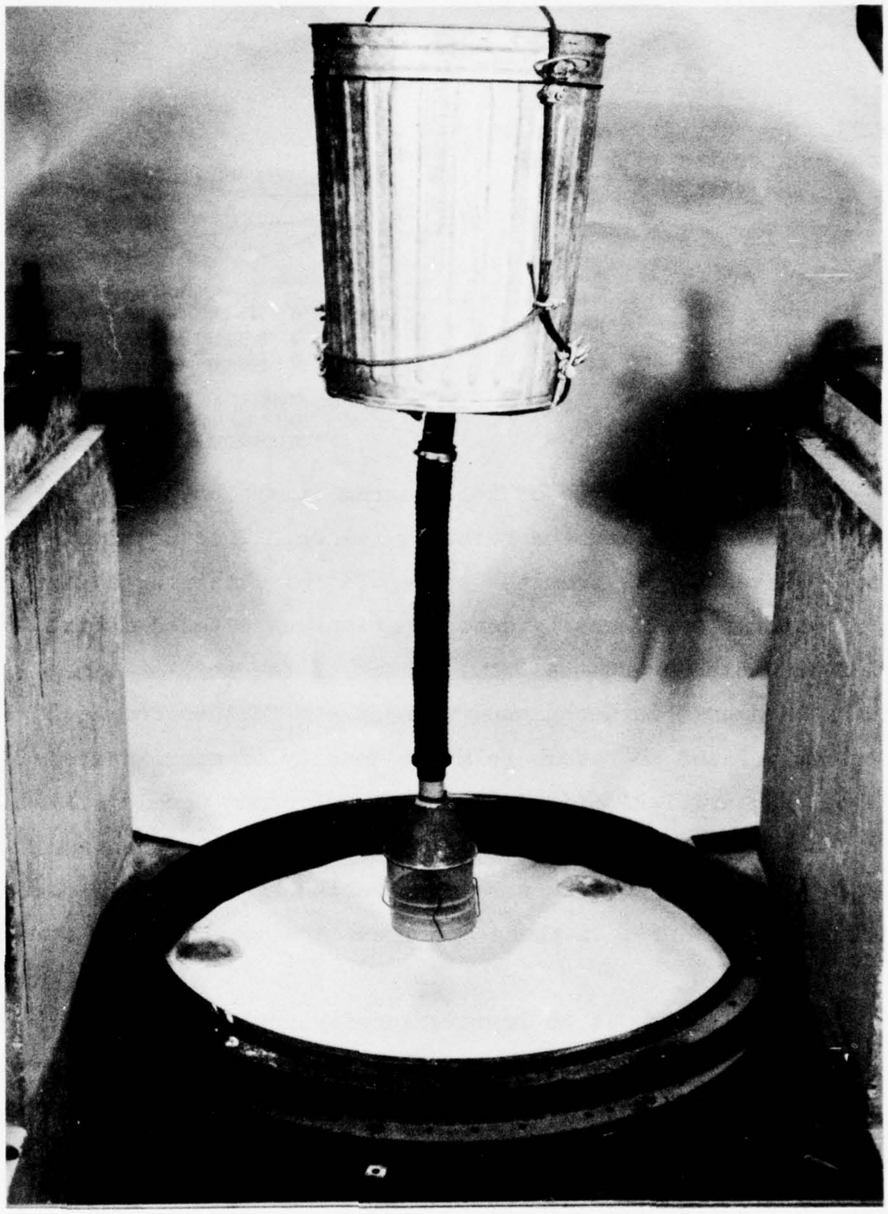

Figure 24. Single-hose rainer

in this manner was undesirable, but did not greatly affect the density results. This technique produced homogeneous deposits, variations being on the order of ±0.5 pcf; however, only medium dense specimens could be constructed using this rainer.

86. The final rainer is depicted in Figure 25. The webbed reinforced circular portion of the rainer serves as a reservoir for the sand. The bottom plate of the rainer is perforated by 3/16-in.-diam holes drilled on a 1-1/2- by 2-in. grid pattern, yielding a plate porosity of 1.4 percent. Variation in lift density was achieved by varying the height of fall.

87. A lift of sand was placed by first resting the rainer on the previous lift, filling the reservoir with a sand bucket, and then hoisting the rainer to the predetermined height of drop by an overhead crane, Figure 26. Stainless steel guide rods were used to limit horizontal translation and rocking of the rainer during the hoist and raining, as it was observed that any rainer movement resulted in density variations. The travel time required for the rainer to reach the desired drop height was recorded, and the amount of sand deposited during this period was estimated. Under no circumstances was the amount of sand rained during travel in excess of 10 percent of the total lift weight. Once the desired drop height was reached, the sand was allowed to fall freely to the specimen surface. The rained surface reflected the pattern of hole spacing in the perforated plate, and a shallow trough was generated along the soil-ring wall interface, Figure 27. This trough was brought to grade at the conclusion of density testing by hand placement. This procedure was repeated until the specimen was constructed to the desired height. Lift densities were found to be a function of the intensity of the falling sand and the height of drop.

88. Plate porosities of 1.4, 2.7, and 4.9 percent were tried; the plate porosity of 1.4 percent produced the most homogeneous lifts. A curve was developed for each plate porosity relating dry density to height of drop. The relationship obtained for the 1.4 percent porosity plate indicated that the dry density is highly sensitive to changes in drop height between 20 and 30 in., Figure 28.

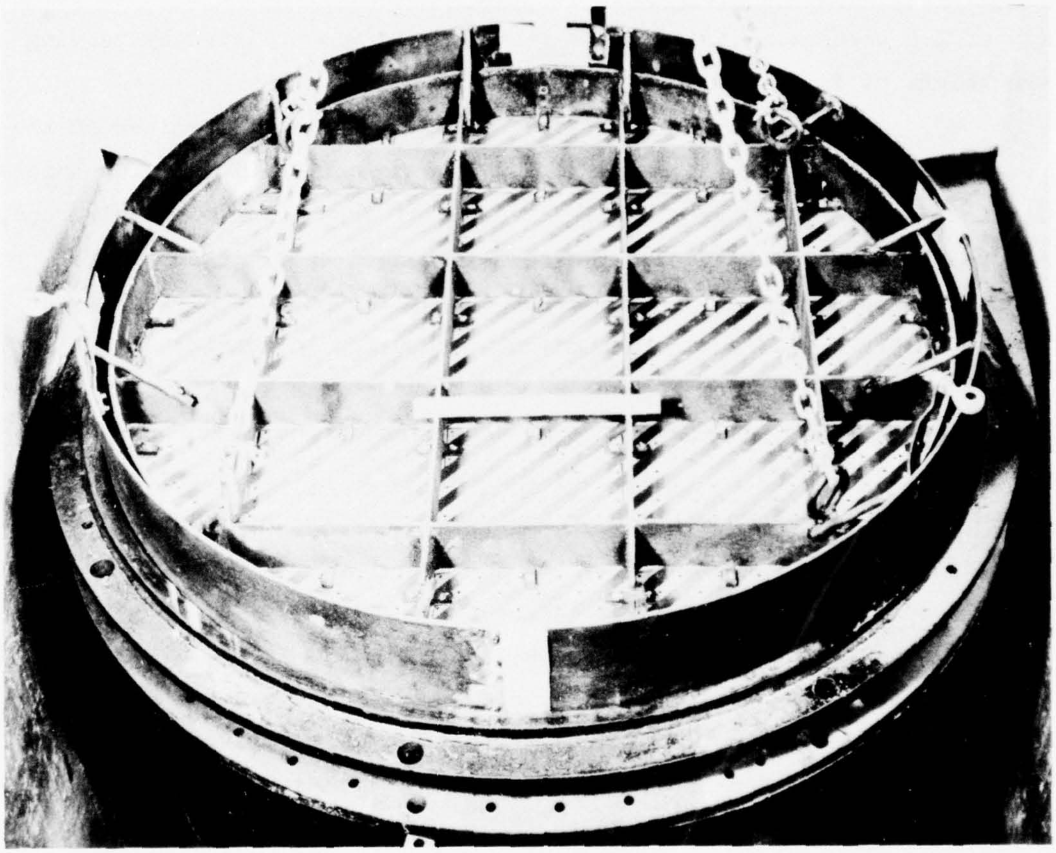

Figure 25. Circular rainer

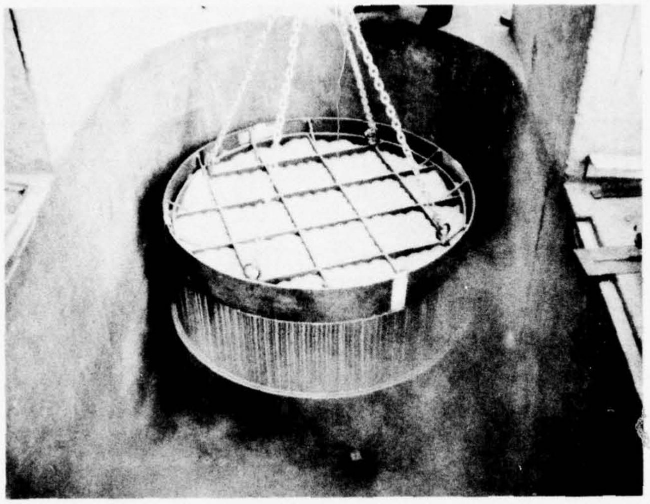

Figure 26. Sand in the process of being rained from the desired drop height with the circular rainer

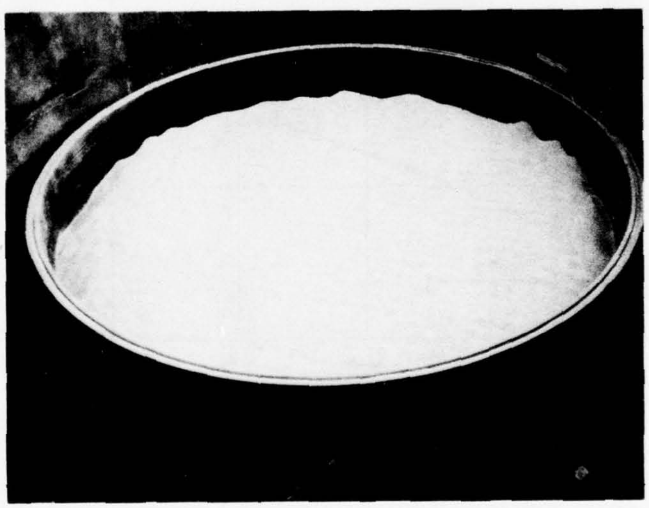

Figure 27. Typical surface formed by raining sand with the circular rainer

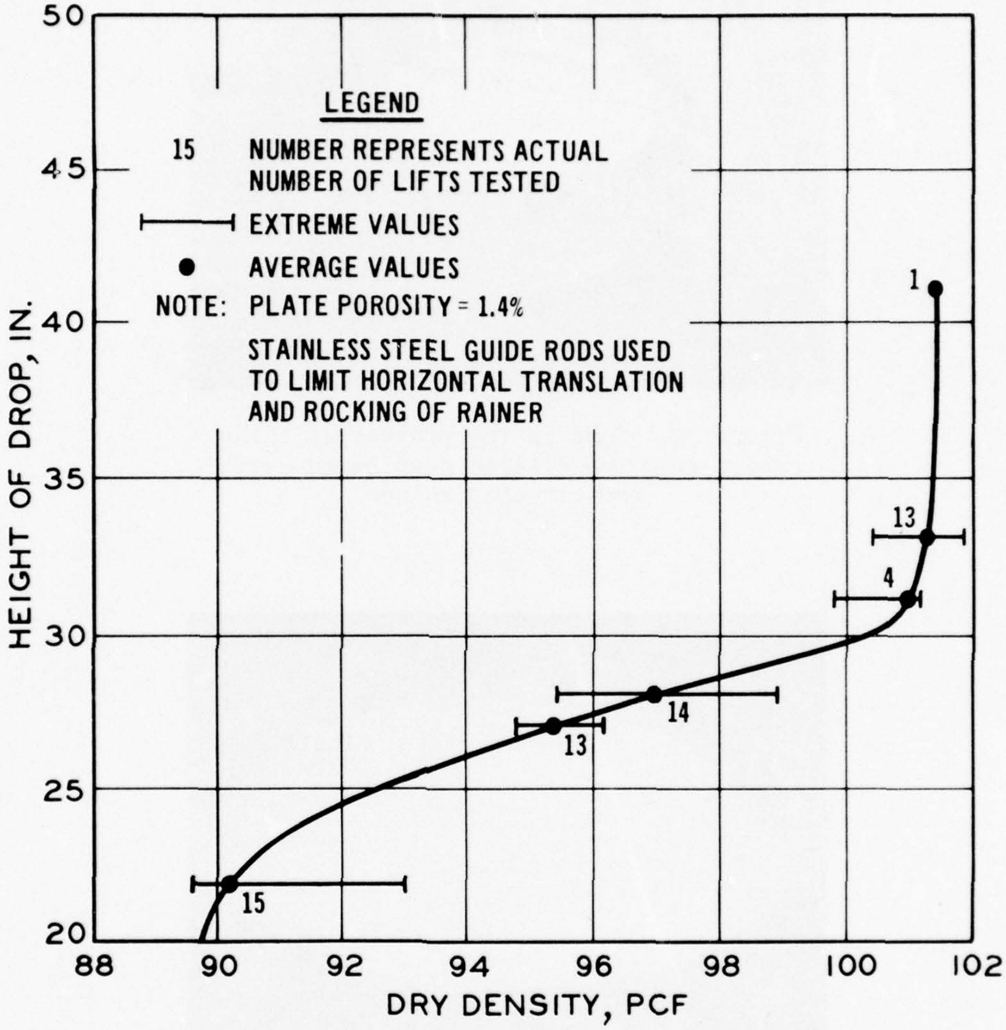

Figure 28. Sand placement with circular rainer; dry density versus height of drop

89. Figure 29 is a plot of density versus radial distance for the

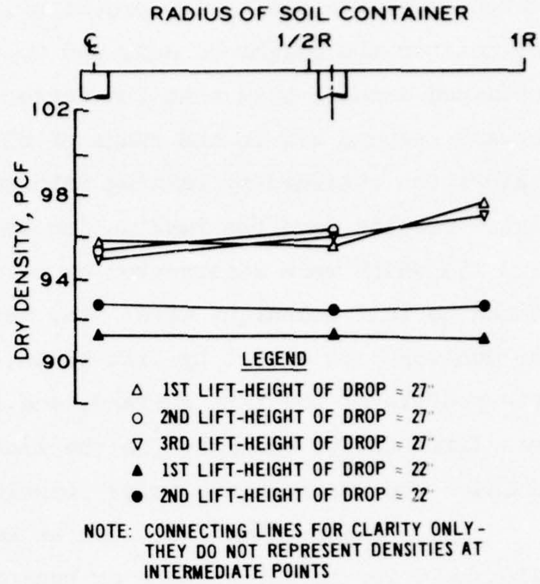

Figure 29. Dry density variation in lifts constructed with circular rainer

circular rainer. The results are shown for drop heights of 27 and 22 in. The plot shows that the three lifts rained from 27 in. are repeatable and uniform within acceptable limits. The two lifts rained from 22 in. are both uniform; however, the lift densities were not as repeatable.

Submergence

90. As described previously, the majority of test specimens were submerged by the upward seepage of water from a water hose buried in a filter beneath the specimen. The degree of saturation of a specimen prepared this way was found to lie in the range of 83 to 93 percent. Percent saturation was determined from samples taken with a miniature Hvorslev fixed-piston sampler. Since the possibility of drainage from the sampler was great, it is thought that this range of percent saturation is the lower bound.

91. Raining into water appeared to offer a more effective way of preparing specimens having a greater degree of saturation. A miniature solid wall soil container was designed to study the effectiveness of the

two techniques. The miniature container had a provision for upward submergence comparable to the prototype, but with this model it was possible to monitor the weight of sand and volume of water used. The results obtained demonstrated that the degree of saturation attainable through upward seepage was in the range of 83 to 97 percent, and the percent saturation obtained by raining into water was approximately 97 percent. These results were the impetus for the four tests (tests 9, 10, 14, and 15) which were constructed by raining into water. The major drawbacks to this technique were: (a) the density of the specimen could not be monitored on a lift by lift basis, (b) it was not possible to observe the profile of the lift surface, and (c) densification of the specimen was difficult to control. In the final analysis, it was decided to abandon the raining into water technique.

92. Other solutions, such as saturating the specimen with carbon dioxide prior to submergence or backpressuring the specimen, did not appear viable due to the size and configuration of the test facility. Therefore, the results reported herein are for submerged specimens with a degree of saturation between 83 and 97 percent.

PART V: TEST RESULTS

General

93. This section of the report contains the results of the individual tests. A summary of the test program is contained in Table 1. The table includes information of a general nature regarding the preparation and testing of the specimens. Preceding the presentation of the test results, certain details of the program common to more than one test are reviewed.

94. Two sands were used in the conduct of the test program, Reid Bedford Model and Ottawa sands. Each test specimen was constructed by lifts to a predetermined density. The construction technique varied by the type of rainer, and any provision employed to achieve a higher density. The rainer types and methods of compaction were described earlier. Table 1 cites the methods of specimen preparation for each test in the program. Beginning with test 4, box density determinations took the place of bulk density measurements.

95. Four test specimens (tests 9, 10, 14, and 15) were constructed by raining dry sand into water. All other test specimens were rained dry. Except for test 3, the specimens were submerged during the performance of the various sampling operations. Test 3 was submerged initially, allowed to drain, and then tested in a drained condition.

96. Many of the test specimens were penetrated at two or more testing pressures. The pressure or pressures at which a test was performed are indicated in Table 1. The usual procedure of testing with two or more pressures is referred to as stage testing and was accomplished as follows:

- a. With the initial test pressure applied (usually 10 psi), an undisturbed sample was taken in the center hole from 0 to 2 ft with a Hvorslev type undisturbed sampler. Each time a hole was advanced, the void produced by sampling was immediately stemmed with a suitably sized steel rod to check sloughing. The next sampling operation was performed in a peripheral hole at the same pressure. This was a series of SPT's for the full depth of the specimen.

b. The overburden pressure was increased to a second testing pressure (usually 40 psi) and the Hvorslev type undisturbed sampler used to obtain a sample from 2 to 4 ft in the center hole. A series of SPT's were then run in a second peripheral hole for the full depth of the specimen at that pressure.

c. The overburden pressure was increased to the last testing pressure (usually 80 psi) and a final drive was made with the Hvorslev type undisturbed sampler from 4 to 6 ft in the center hole. The final series of SPT's were then made at the same testing pressure in the last peripheral hole for the full depth of the specimen.

97. Tests 2-5 were stage tested as described above. Tests 6 and 7 were also stage tested; however, these tests were performed on specimens having an overconsolidation ratio (OCR) of three.

98. Overconsolidation was accomplished by elevating the water bag pressure to three times the testing pressure for one-half hour, and then reducing the pressure back to the testing pressure. Tests 25 and 26 were stage tested at two pressures.

99. Upon completion of sampling, the equipment was disassembled and the specimen was hand shoveled out of the stacked-ring facility. Every test specimen was constructed with fresh sand obtained from a WES stockpile of that particular material. Grain size distribution curves and maximum-minimum density tests were frequently performed to ensure that the sand remained fairly constant.

100. Density determinations were sometimes made during the tear-down phase. A direct comparison of placement densities with tear-down densities is limited in value, since the specimen had been subjected to much disturbance during the testing phase.

101. Water bag pressure readings were observed during the drive, recovery, and washout operations. It was noted that the water bag pressure decreased for each operation on the order of 1 to 6 psi, depending on the applied pressure. This pressure drop is attributed to lateral yielding around the void produced during sampling. Since the pressure drops were consistent, no detailed analysis was made; however, they do indicate the probability of a change in specimen condition between sampled holes.

102. It is observed that several variables were introduced by the physical limitations of the test facility and the inability to construct truly homogeneous specimens. In addition, there are other suspected forces at play which will be called variables, that could not be measured. These variables make it difficult, if not impossible, to sort out the operating parameters in a given test, and the extent to which they affect the results. A list of these variables is given in Table 2 to aid the reader in an intelligent appraisal of the test data.

Tests 1-26

General

103. Observations regarding the test data are confined to the results of the second and third SPT for each hole advanced. The first and last drives were disregarded as they were thought to be adversely affected by the proximity of top and bottom boundary conditions. Twenty-six plates corresponding to the 26 tests follow the References section in this report. They depict the data collected for each test.

Test 1

104. The results of test 1 are depicted in Plate 1. The density was determined by dividing the total weight of sand deposited in the soil container by the volume of the specimen. A series of four split spoon drives were made through each access hole into the specimen to observe the effect of boundary conditions and sampling sequence on the test results. The sampling was first conducted in the center hole, then each of three peripheral holes, at 40-psi overburden pressure. The results of this initial test were greatly scattered, much more so than subsequent tests of the same nature. This scatter was, in all likelihood, a result of inexperience in specimen construction. Since the results are suspect, very little could be concluded regarding the effect of boundary condition.

Test 2

105. The density was determined from the bulk weight and volume

of the specimen (Plate 2). The N-values of the midregion increased with increasing overburden pressure. The final drive at 40 psi was not completed because the hole had been inadvertently overwashed during the cleanout operation of the previous SPT. The blow counts for 0-6 and 6-12 in. are shown. The N-values plotted at the 1-ft level may have been affected by the overburden head.

Test 3

106. This specimen was submerged for a minimum of 24 hr after construction, and then permitted to drain before testing. The purpose of this test was to evaluate the influence of the groundwater table on N-values. Moisture determinations made at the end of the test indicated an average moisture content of 15.3 percent. The drained test results are compared with submerged test results in a subsequent section.

Test 4

107. Density determinations with the box density device were begun with this test. The vertical profile of density determinations indicates that the specimen was fairly uniform in the locations observed. It should be noted, however, that the rotating rainer yielded specimens which varied in density along the radius of a lift (see Figure 23). A definite increase in penetration resistance was observed with increasing overburden pressure.

Test 5

108. The density determinations were fairly uniform for the locations checked. Only two of the three peripheral holes were sampled due to difficulties with the water bag device at the 80-psi testing pressure. The N-values again increased corresponding to the increase in overburden pressure.

Test 6

109. This test was performed on a specimen consolidated to 3 times the testing pressure. The penetration resistance increased with overburden pressure (Plate 6). The overconsolidated test results are compared with the normally consolidated test results in a subsequent portion of the report.

Test 7

110. Test 7 was also conducted at an OCR of 3. The N-values increased corresponding to the increases in overburden pressure.

Test 8

111. Test 8 was performed as a check of test 1. Malfunctions with the testing equipment occurred; however, enough data were generated to make a critical comparison. The N-values from test 8 were significantly lower and less scattered than the results of test 1. It is concluded from this that the results of test 1 suffered from specimen construction inexperience. The results of test 8, however, are considered more reliable in view of the experience gained. The data displayed in Plate 8 may represent the effect of sampling in close proximity.

Test 9

112. Test 9 was conducted on a specimen which was rained into water. The densities reported in Plate 9 were determined during the tear-down phase. The N-values were surprisingly consistent considering the method of specimen construction and the after-testing density profile.

Test 10

113. This was another test performed on a specimen constructed by raining into water. A higher density was achieved for this test by rodding each lift with a 2-in.-diam hollow pipe. The technique of rodding the specimen was used after an attempt to vibrate the specimen did not provide the desired results. Vibrating the specimen was accomplished by resting the vibrator (Figure 30) on two 2- by 12-in. planks placed across the top ring of the stacked-ring container. The vibrator was sandbagged for stability and coupling. The vibrations caused a thin (1 to 2 in.) crust to form on the lift surface, while beneath this crust, the sand remained in a loose condition. The low density profile at the base of the soil container resulted because several lifts were placed and vibrated before changing over to the alternate rodding technique. The agreement between N-values was less favorable than observed in test 9.

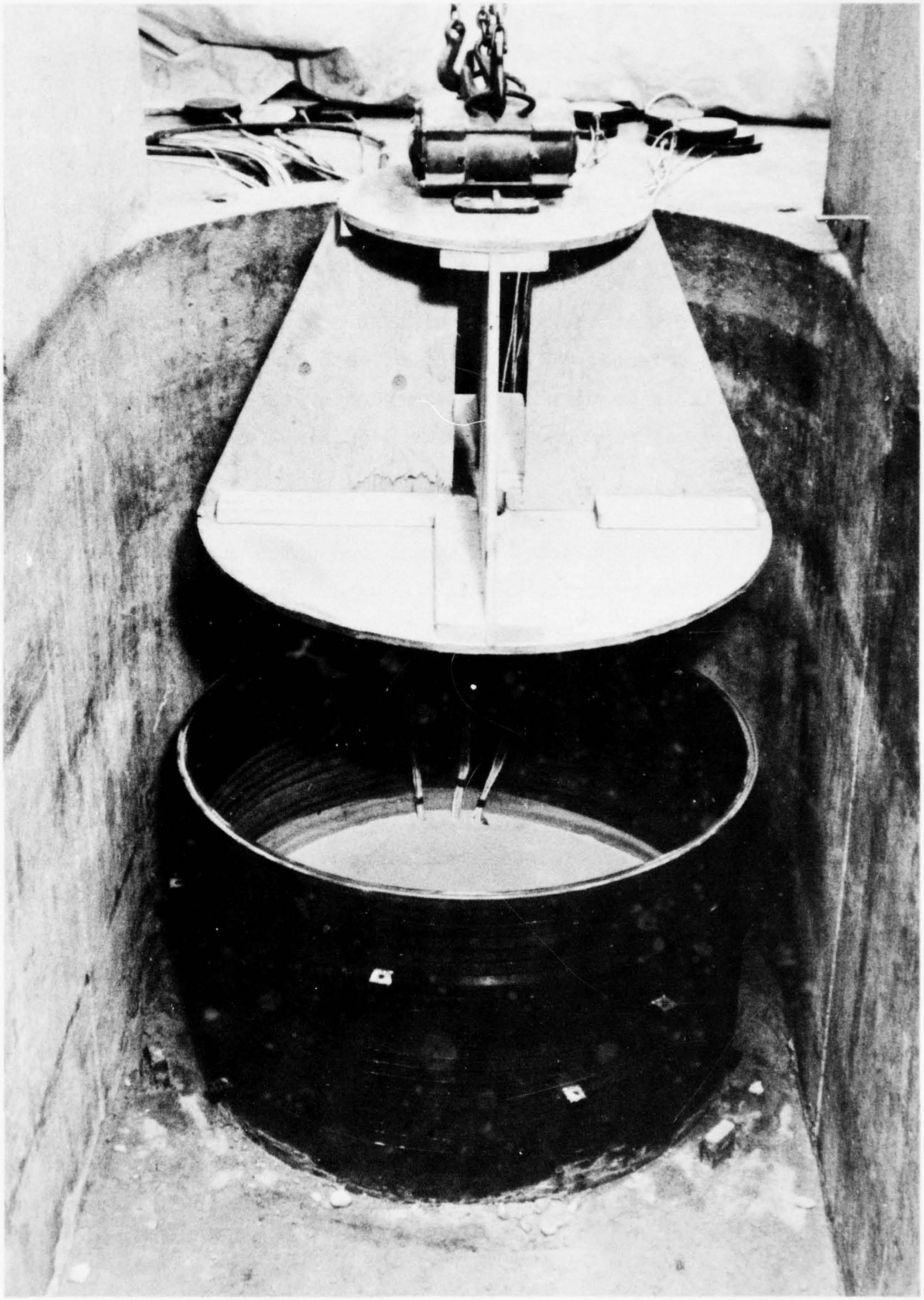

Figure 30. Vibratory compactor

Test 11

114. Density determinations were made during the placement and tear-down phases of this test. The maximum variation was on the order of ±1.0 pcf. This difference in density is minor and can be attributed to that amount of variation initially or sampling disturbance. The agreement between the peripheral hole N-values is good. The lower N-values obtained for the center hole indicate the possibility of different test conditions between the center and peripheral holes.

Test 12

115. This specimen was tamped to achieve a high density condition. Tamping with a 1-ft-square plate is felt to induce residual lateral stresses in the specimen. Although systematic, the tamping effort is dependent upon human capabilities and is therefore not exact. This fact may account for the spread of blow count data at the 2.5-ft level (Plate 12). Two series of density determinations were made. The trend of the after-testing density determinations indicates a general loosening of the specimen. This condition was made possible by the void produced during sampling. Although stemmed with a steel rod, the irregular surface of a borehole made it impossible to completely fill the void.

Test 13

116. After-testing density determinations were recorded along with placement densities for this test also. The two density profiles correspond more closely than those of test 12. The N-values increased from hole 1 to hole 3 (Plate 13). This trend displays what might be interpreted as a change in the specimen condition due to the sampling sequence.

Test 14

117. Specimen construction for test 14 was accomplished by raining into water and subsequent rodding. Density determinations were made after testing. The N-values recorded are somewhat erratic, possibly indicating gross density variations throughout the specimen. Compared to test 10, it was observed that the average results of test 14 were approximately 16 percent less than the N-values recorded for test 10. The average after-testing densities recorded for these two

tests were very nearly the same. This large data spread is not upheld by the test data derived from specimens rained dry. The rained into water test data are viewed as unreliable.

Test 15

118. The specimen built for test 15 was also constructed by raining into water and rodded with a 2-in.-diam open-end pipe. The results of this effort are shown in Plate 15.

Test 16

119. Test 16 was a low-density specimen which produced an average penetration resistance of approximately 1 blow per foot or less. A previous test, test 4, had involved a slightly lower average density; however, it produced an average of 3 blows per foot. Since both specimens were constructed with the rotating rainer, the reason for the discrepancy is not readily apparent. It may be related to the fact that test 4 was the first test specimen checked with the box density device. It is thus possible that the density determinations for test 4 were inaccurate. The data spread is not attributed to the SPT, which is considered a reliable measure in homogeneous deposits, based on later tests.

Test 17

120. This test specimen was tamped to achieve a high density condition as in the case of test 12. Two profiles of density determinations are shown in Plate 17. These display a less dense condition following testing and may in part account for the variation in N-values. As mentioned previously, the tamping procedure is not precise, and may also contribute to the variations observed. The final drive of the center hole was not made.

Test 18

121. Test 18 specimen was manually tamped to achieve a greater density as in the case of tests 12 and 17. The average placement densities for tests 17 and 18 are nearly equal. In test 17, the N-values were less for the peripheral holes than for the center hole. In test 18, the N-values increased according to the order of sampling. This reverse in trends may be related to the pressures at which the specimens were tested (10 psi in test 17 and 80 psi in test 18).

Test 19

122. The single-hose rainer was used to construct this specimen. Good agreement exists between the peripheral holes; however, the center hole results are lower. Density nonhomogeneity is not considered the major contributing factor for this discrepancy, since the single-hose rainer was found to place fairly uniform lifts.

Test 20

123. The specimen constructed for this test was the first specimen built with the circular rainer. The vertical density profile was not as uniform as desired. This was due to inexperience with this rainer, and the fact that this specimen was built without the assistance of guide rods. Guide rods were subsequently used to limit the horizontal translation and rocking which had caused density nonhomogeneity within lifts in test 20. It is, therefore, felt that the test 20 results suffer from density heterogeneity. The results, however, were incorporated in the statistical analysis presented later. Compared to test 8, the results of test 20 appear at least as consistent as test results derived from specimens built with the rotating rainer. These results further illustrate the unreliability of test 1.

Test 21

124. The specimen for this test was constructed with the circular rainer using the guide rods to limit horizontal translation and rocking. The vertical density profile is somewhat better for this test. More important, however, from what was observed regarding the placement capabilities of this rainer, the horizontal density profile of each lift is more consistent than achieved in the past. The more repeatable penetration resistance values of this test and later tests are credited to density homogeneity.

Test 22

125. The center hole of this test was first sampled with the undisturbed sampler. Two peripheral holes were subsequently sampled with the split spoon. The N-values recorded for the two peripheral holes were repeatable.

Test 23

126. The center hole of this test was sampled with the undisturbed sampler, and SPT's were performed in two peripheral holes. Plate 23 depicts the penetration resistance with depth; the N-values were repeatable.

Test 24

127. The N-values in the middepth of the specimen were repeatable. The cause of the discrepancy between the N-values at the top of the specimen is unknown.

Test 25

128. This test specimen was constructed with Ottawa sand and was stage tested at 10 and 40 psi. Undisturbed samples were obtained from the center hole; two peripheral holes were sampled with the split spoon.

Test 26

129. Test 26 was conducted to duplicate test 25. These two tests are significant in that they confirm the repeatability of the SPT when used in carefully prepared laboratory specimens. A comparison of these two tests is made in a subsequent section of this report.

PART VI: DISCUSSION OF RESULTS

130. The penetration resistance of a particular cohesionless material is dependent upon the relative density and applied overburden pressure. This was demonstrated at the Bureau of Reclamation by Gibbs and Holtz. Likewise, the WES data display a similar trend; that is, as density increases, penetration resistance increases, and as the overburden pressure is increased, so is the N-value increased. WES data also generally support Schmertmann[28] in showing an increase in resistance for each 6-in. increment of a drive.

131. Results of the WES study will be compared to the Gibbs and Holtz correlation curves in a subsequent section. Prior to making such a comparison, it is interesting to study the relationship between individual data points. The analysis of the data is complicated by the many variables in the testing program. These variables include the method of specimen construction, the overburden pressure, the overconsolidation ratio, the drainage condition, the specimen condition changes which occur during testing, and the type of sand. To analyze the effects of these variables on the penetration resistance, data plots have been prepared for each of the three overburden pressures.

10-psi Overburden Pressure

132. Table 3 summarizes the data used to obtain Figure 31, which shows the relationship between N-values and relative density at 10 psi. Two sands, Reid Bedford Model and Ottawa, are represented. Data points were selected from the middle region of the stacked-ring facility, and corrected for overburden pressure. The symbols indicate the procedure used in the specimen construction.

133. The 10-psi plot exhibits a marked spread in penetration resistance between the two sands. N-values derived from the SPT's in Ottawa sand are well below the N-values of the Reid Bedford Model sand at the same relative density. It appears from this that grain shape may have an effect on the recorded penetration resistance. The spread

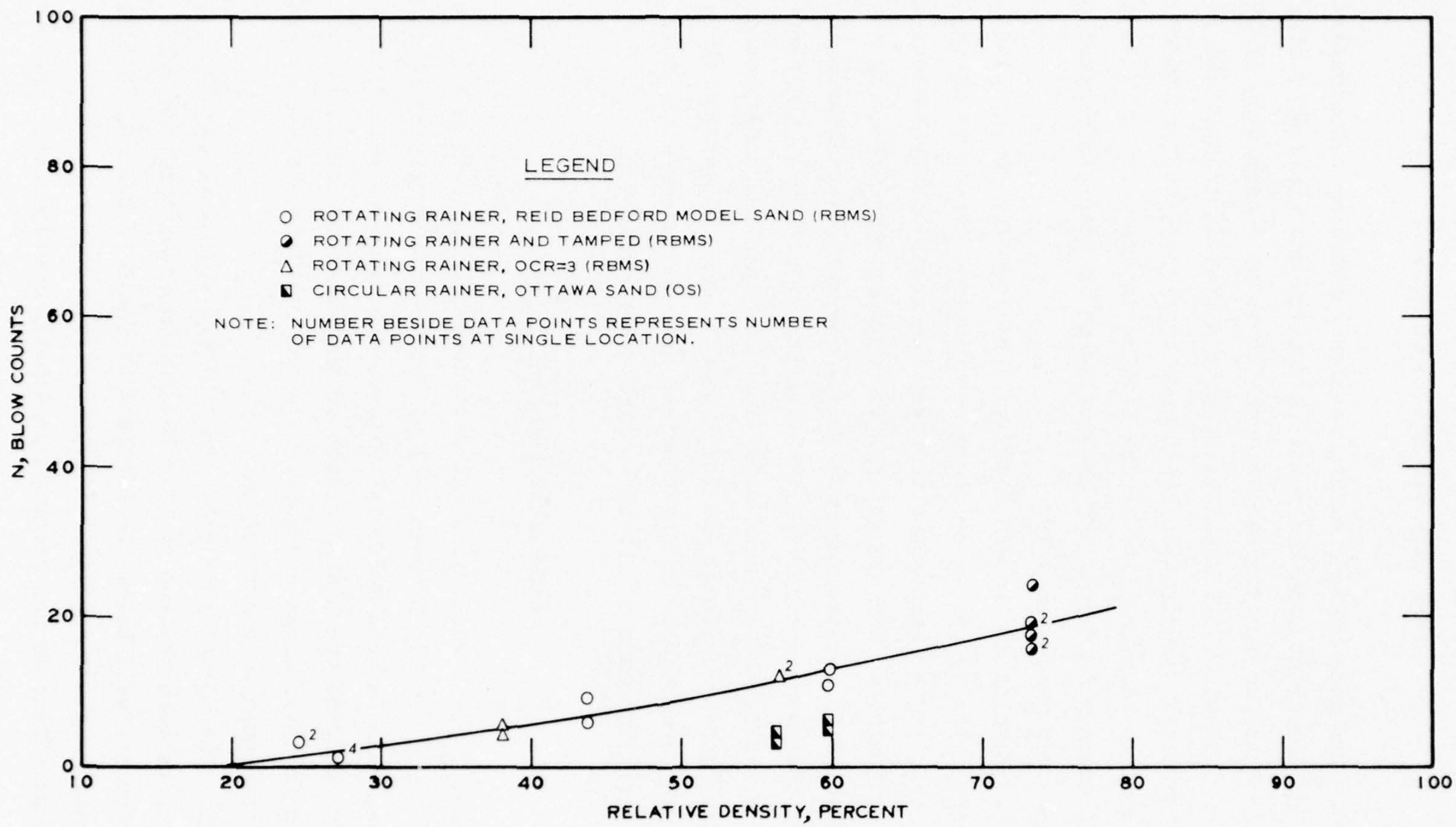

Figure 31. SPT N-values versus relative density at 10-psi overburden pressure

also may have resulted from the method of specimen preparation; hence, two primary factors, grain shape and specimen construction, are likely responsible for the variations.

134. It is interesting to note that at the 10-psi overburden pressure, overconsolidation of the specimen constructed with the rotating rainer yields the same magnitude of penetration resistance as those specimens constructed with the rotating rainer and normally consolidated. Furthermore, the results of the tamped specimen fit the trend reasonably well.

135. Under these test conditions, it is tentatively suggested that: (a) lightly overconsolidated deposits have little effect on the penetration resistance, and (b) the sand type and/or the method of specimen preparation are influential in determining the penetration resistance. The proximity of the data points also suggests that the SPT is reasonably repeatable under controlled laboratory conditions.

40-psi Overburden Pressure

136. Table 4 summarizes the data obtained at the testing pressure of 40 psi, and Figure 32 presents this data. The plot contains the results of 20 individual tests, and is the most comprehensive of the three testing pressures.

137. The legend in Figure 32 indicates the method of sample preparation. In addition, the drained test results, the overconsolidated test results, and the Ottawa sand test results are shown in relation to all test data at 40 psi.

138. Two curves are shown: (a) one passing through the average of data derived from specimens constructed with the rotating rainer, including the tamped specimen data, and (b) an average line fitting the data corresponding to specimens constructed with the circular rainer and the single-hose rainer. If the data derived from tests 1, 3, 6, 7, 9, 10, 14, and 15 (the initial test, the drained test, the overconsolidated tests, and the "rained into water" tests) are neglected, as replotted in Figure 33, the trends are more clearly defined. The two trends

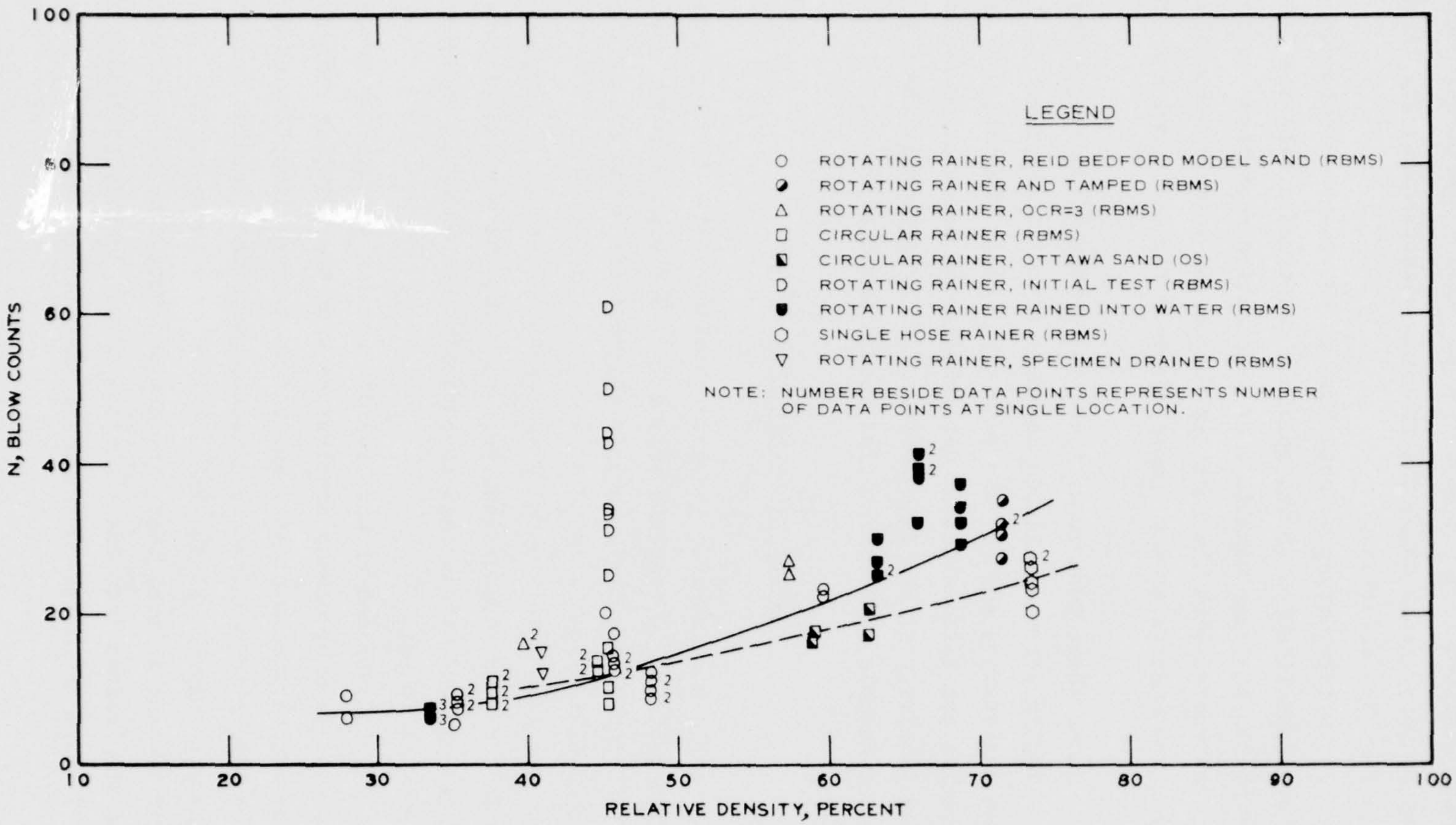

Figure 32. SPT N-values versus relative density at 40-psi overburden pressure

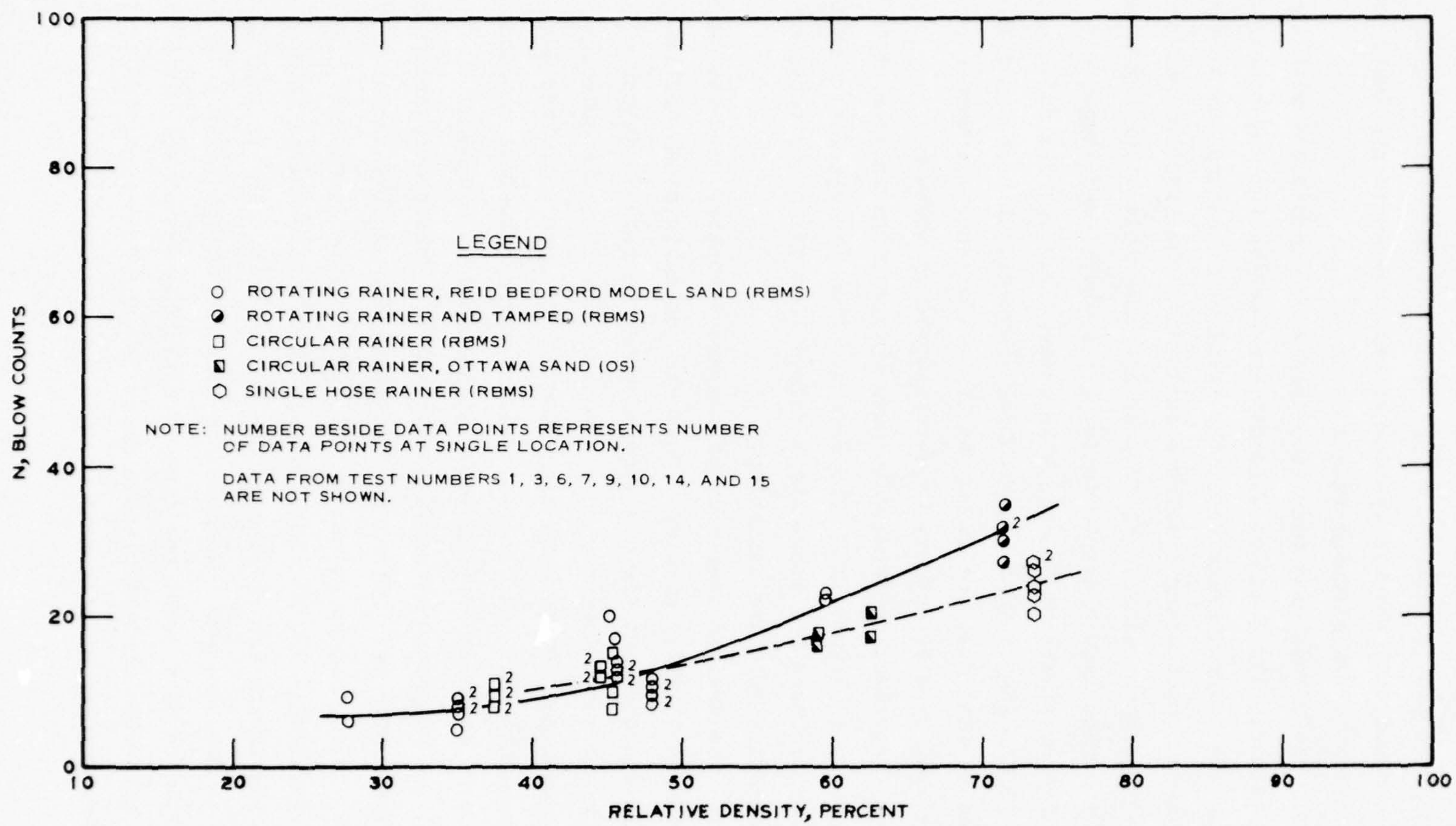

Figure 33. SPT N-values versus relative density at 40-psi overburden pressure

appear well substantiated considering data derived from individual tests are tightly grouped in contrast to the spread of the overall plot. It has been assumed that the single-hose rainer constructs specimens in a manner similar to the circular rainer.

139. The Ottawa sand test specimens were constructed with the circular rainer. The N-values derived from testing the two specimens fall along the lower average line, the trend representing the average data obtained from testing specimens built with the circular rainer and the single-hose rainer. It is possible that this illustrates less dependency on the sand characteristic, grain shape, and suggests that the specimen construction technique is responsible for the difference observed at the 10-psi testing pressure. However, this is not substantiated by the data, and it may be that at greater overburden pressure, the sand type effect may be overshadowed by pressure.

140. Prestressing appears to have greater significance at this testing pressure (Figure 32). The N-values from the two test specimens with an OCR of three lie above the N-values from all other tests at their respective relative densities.

141. The drained test results compare favorably with the other data, although slightly greater. This was not anticipated and intuitively one would expect the presence of water to have a greater effect. This favorable comparison may be due to the fact that the submerged specimens were not 100 percent saturated. With such a limited data base it does not seem judicious to venture any conclusions concerning the effect of submergence (degree of saturation) on N-values.

142. A comparison was made between the N-values obtained from testing the center hole (first hole in sequence) and the second peripheral hole (third hole in sequence) drilled. Figure 34 depicts the differences observed. The circles represent N-values obtained in the mid-depth region during the driving of the center hole. The triangles are the results for the same region of the specimen in the third hole drilled. Below 50 percent relative density, the center hole data lie slightly below the peripheral hole data. Above 50 percent, the positioning and scatter of both sets of data are similar. In the lower

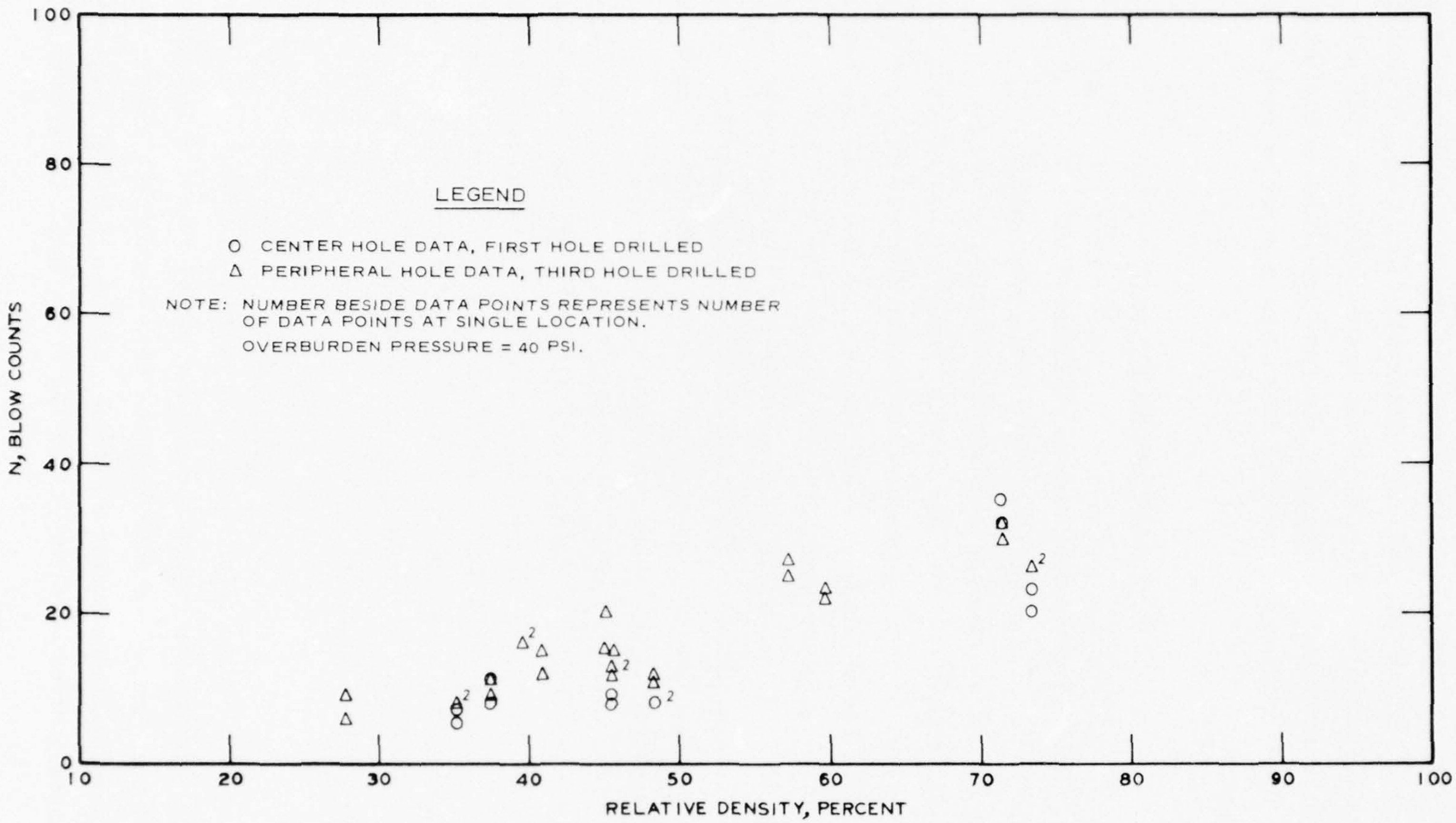

Figure 34. Data plot comparing results of the center hole and the second peripheral hole drilled

density range, the variation in the two data trends possibly represents the effects of variables previously discussed, i.e., specimen condition changes due to sampling. No attempt was made to collapse this data based on this observation because of the many variables in the testing program. The variables are cited in Table 2 of a previous section of this report.

80-psi Overburden Pressure

143. Table 5 presents the data obtained at the testing pressure of 80 psi. Figure 35 is a plot of this data. The variation in results due to the manner of specimen construction is clearly defined at this pressure, since only one sand was tested. Lower values of penetration resistance resulted from specimens constructed with the circular rainer, as compared to the N-values derived from testing specimens constructed with the rotating rainer. The SPT, as performed in the laboratory for this study, appears sensitive to changes in structure caused by various methods of sand placement. This implies that geologic factors related to deposition or, possibly, previous overburden loading are among the variables measured by SPT values obtained in the field.

144. The test specimens having an OCR of three yielded N-values slightly greater than the normally consolidated specimens. The sensitivity of the SPT to low OCR values in these tests was slight; hence, it appears that one would experience difficulty trying to establish the stress history of a site from field N-values. The drained test results are in agreement with the results of the submerged tests. However, the data are too sparse to be definitive.

Summary

145. Penetration resistance as affected by relative density and overburden pressure is the main theme of this report. It should, however, be noted that the manner in which a specimen has been prepared will ultimately affect the results of the SPT. This is fairly well

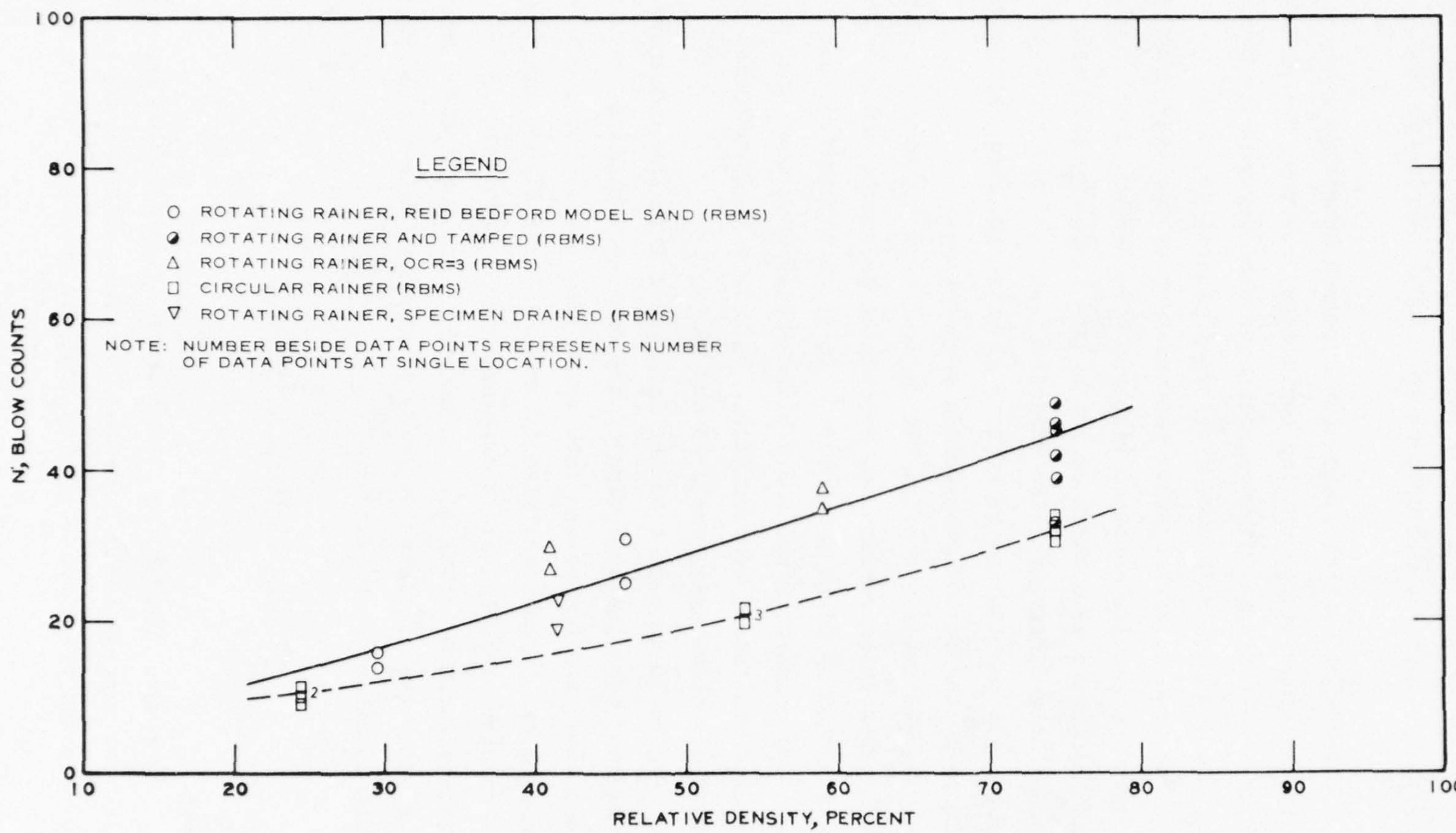

Figure 35. SPT N-values versus relative density at 80-psi overburden pressure

illustrated by the results plotted in Figures 33 and 35, and variations are presently attributed to differences in lateral stress and soil structure.[41]

146. Overconsolidation of the test specimen generally yielded slightly higher values of penetration resistance; however, the ability of the SPT to detect slightly overconsolidated sand deposits in nature is dubious, considering the nonhomogeneity of natural deposits.

147. The results of the tests performed on Ottawa sand compare favorably with the results obtained with the Reid Bedford Model sand, using relative density as a basis of comparison since the two sands are not appreciably different. The variation depicted on the 10-psi plot is probably a combination of effects of which the most influential is believed to be the method of specimen preparation.

148. The WES results confirm the concept of a systematic relationship between penetration resistance, overburden pressure, and relative density established by Gibbs and Holtz.[6] It is also observed that under laboratory conditions and for a given homogeneous test specimen, the SPT N-value was fairly reproducible. This is well illustrated by the two tests on Ottawa sand, tests 25 and 26.

149. Figure 36 is a plot of the data taken from the three overburden pressures, with the exception of the drained test data, the initial test data, and the rained into water test data. The scatter and overlapping of the data are significant. If this figure was used to predict relative density, it is apparent that a broad band of probable values would be obtained. In addition, one would also have to take into account the standard deviation inherent in determining relative density as discussed by Tavenas.[30]

Statistical Analysis

Introduction

150. Data were analyzed for the purpose of determining the equations which best express the relationship between SPT N-values, relative density, overburden pressure, etc. The analysis provided: (a) a list

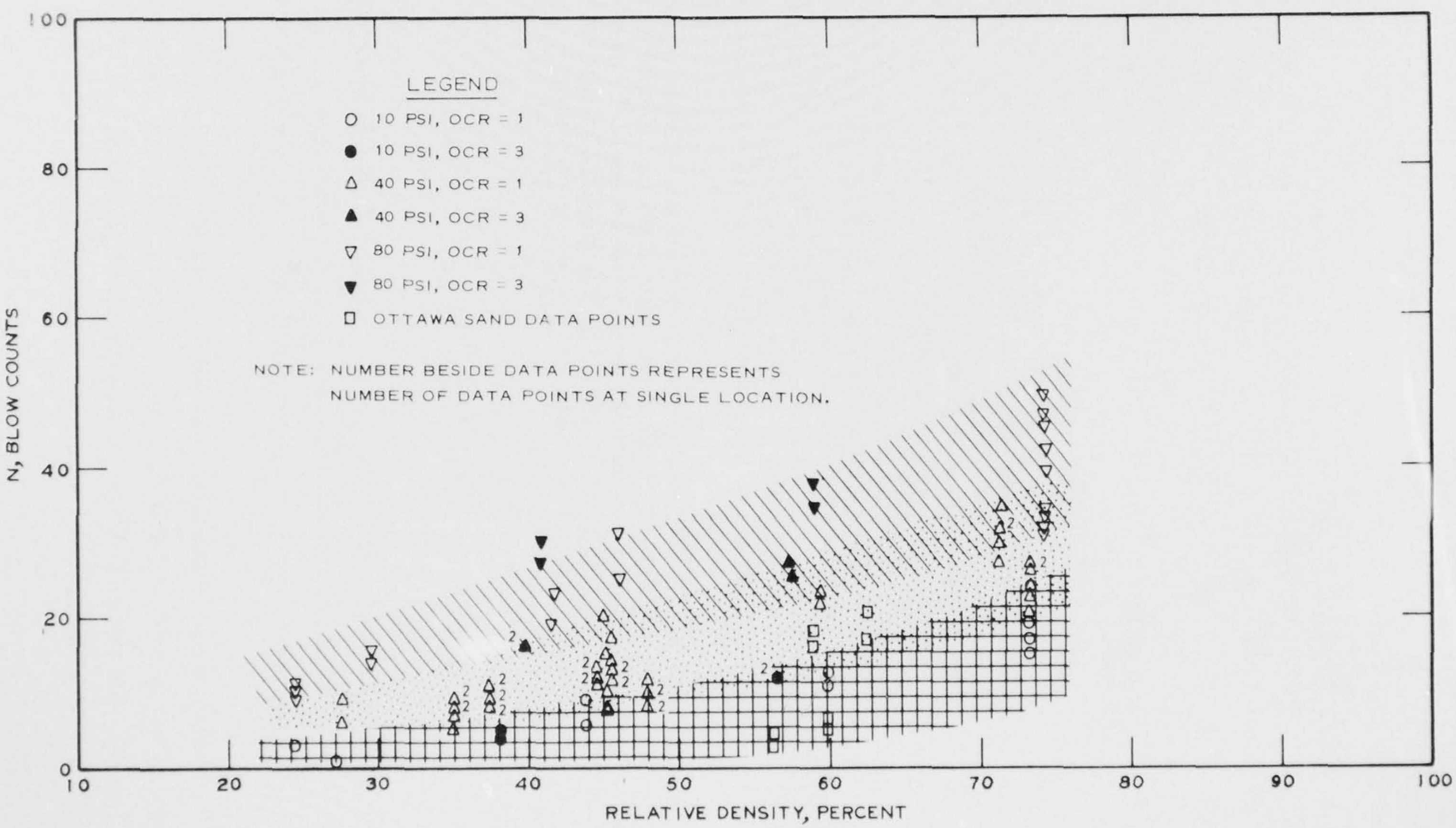

Figure 36. A depiction of the spread of WES data for the three overburden pressures

of parameters which were correlatable with the SPT N-values and/or relative density, and (b) equations which show the relationship between the parameters and N-values.

Computer program characteristics

151. The multiple regression computer program used for the analysis is capable of handling up to 75 variables. In general, the computer program has four basic steps in its operation:

a. Step 1. Values of the basic independent variables are fed in and values of the combined variables are generated.

b. Step 2. The simple statistics, i.e., sum, mean, sum of the squares, variance, and standard deviation of each variable, are computed. A bivariant analysis is conducted, i.e., each variable is correlated with every other variable one at a time. This indicates which of the variables are interrelated.

c. Step 3. For each dependent variable specified the computer searches the independent variables (first taking one at a time then two at a time and so on) and lists the individual variables and combinations of variables that correlate best with the independent variable. A list of variables that correlate best is termed models by the program.

d. Step 4. Based on the models generated, the independent and dependent variables are specified and a Doolittle matrix inversion technique is used to generate the regression equation of best fit through the data. This equation is in the form:

$$y = b_0 + b_i x_i + b_i + 1, x_i + 1 \ldots b_n x_n$$

152. The computer program was written by Mr. James H. Goodnight[42] of the Department of Experimental Statistics, North Carolina State University. It was executed on a Honeywell GE-635 computer for this study.

153. Tables 6 and 7 contain data generated during the testing program described previously and form the complete data base resulting from the tests. The data in Table 7 were randomly selected and withheld for use in verification of formulated equations, while the data

in Table 6 form the data bank used for the statistical analysis. Some explanation is required regarding the contents of Tables 6 and 7. The first column is Test No. The second column is Sand Type, where the figure 1.00 indicates Reid Bedford Model sand and 2.00 indicates Ottawa sand. The next column is Overconsolidation Ratio, indicating the stress history of the specimen. The next column is Hole No., where the numbers in this column (1-4) refer to the holes in the overburden head (shown in Figure 6) through which the samples could be obtained. The numbers in the Sequence column refer to the order or sequence in which the data were taken, the sequence in which the holes were tested. The column of Corrected Dry Density contains the dry density, corrected for overburden pressure. Relative Density and Vertical Stress are presented in the next columns. The next column, Depth, represents the depth in the sample from which the data were taken and the corresponding Standard Penetration Test N-value is in the following column. The final column is Recovery, and is the percent of sample recovered in the split spoon sample. The number 1.00 is entered in the column if no data were obtained.

154. In order to make a more meaningful statistical analysis some of the data which were generated (Table 6) were considered suspect and deleted from the data bank. These data include all data from tests 1, 3, 9, 10, 14, and 15. The reasons for suspecting this data are as follows:

- a. Test 1 was the first test conducted. The results of this test were greatly scattered, much more so than subsequent tests of the same nature. It is believed that limited experience in specimen construction resulted in a nonhomogeneous specimen.
- b. Test 3 was a drained test, i.e., the sample had been completely submerged and then allowed to drain.
- c. Specimens for tests 9, 10, 14, and 15 were prepared by raining the material into water; thus, the in situ density of the material prior to testing was not obtained. The density determinations were limited to posttest conditions. Thus, the data shown in Table 8 comprise the data used in the statistical analysis, and include both normally and overconsolidated Reid Bedford Model sand data and normally consolidated Ottawa sand data.

155. A regression analysis conducted on these data resulted in the equation:

$$N = -10.4 + 3.2(OCR) + 0.24(\bar{\sigma}_v) + 0.0045(D_R)^2 \quad (1)$$

where

N = Standard Penetration Test N-value

OCR = overconsolidation ratio

$\bar{\sigma}_v$ = effective vertical stress, psi

D_R = relative density

This equation fits the data with a coefficient of determination, r^2, of 0.86, and has a standard deviation of ± 4.9 blows per foot. Table 9 presents the N-values predicted by Equation 1, the N-values observed in the laboratory, and the difference between the predicted and the observed. This table shows that the difference is generally less than 4 blows per foot. Table 10 shows the N-values predicted by Equation 1, the N-values observed in the laboratory, and the difference between the predicted and the observed values for the data shown in Table 7, which were randomly selected and removed from the data bank.

156. Analyses were performed on the data bank to obtain variations of the model. For example, the overconsolidated Reid Bedford sand was omitted (i.e., data from tests 6 and 7) and an equation which fits the normally consolidated Reid Bedford Model sand and Ottawa sand data was generated. This equation:

$$N = -6.5 + 0.23(\bar{\sigma}_v) + 0.0045(D_R)^2 \quad (2)$$

fits the data with a coefficient of determination of 0.85 and has a standard deviation of 4.17 blows per foot.

157. Normally consolidated and overconsolidated Reid Bedford Model sand data were analyzed, i.e., the data from tests 25 and 26 were omitted, resulting in the equation:

$$N = -9.4 + 3(OCR) + 0.23(\bar{\sigma}_v) + 0.0046(D_R)^2 \quad (3)$$

Equation 3 fits the Reid Bedford Model sand data with a coefficient of determination of 0.87 and a standard deviation of 4.03 blows per foot.

158. Finally an equation was developed for normally consolidated Reid Bedford Model sand. Specifically, the data from tests 6, 7, 25, and 26 were omitted. The resulting equation:

$$N = -5.5 + 0.2(\bar{\sigma}_v) + 0.0046(D_R)^2 \qquad (4)$$

fits the normally consolidated Reid Bedford Model sand data with a coefficient of determination of 0.87 and a standard deviation of 4.05 blows per foot.

159. It should be noted that all of these equations have approximately the same form and fit the respective data with a coefficient of determination of 0.85 or better and a standard deviation of approximately 4 blows per foot. This analysis clearly indicates that there is a direct relationship between OCR, vertical stress, relative density for a given grain size distribution, and SPT N-values. The limited Ottawa sand data indicate that for a given gradation, the angularity of the particles may not be a significant variable.

160. An equation of the form $D_R = f(N)$ was desirable since the blow count is the known quantity in practice. A regression analysis conducted for the data in Table 6 produced the equation:

$$D_R = 8.6 + 0.83\left[\left|\frac{N + 10.4 - 3.2(OCR) - 0.24(\bar{\sigma}_v)}{0.0045}\right|\right]^{1/2} \qquad (5)$$

This equation fits the data with a coefficient of determination of 0.78 and has a standard deviation of ± 7.6 percent. Table 11 presents the relative densities predicted by Equation 5, the relative densities which were known to exist during the testing program, and the difference between the predicted and the observed. The maximum difference for the data studied was +18.9 percent. Table 12 shows the relative densities predicted by Equation 5, the relative densities observed in the

laboratory, and the difference between the predicted and the observed relative densities for the data which were randomly selected and removed from the data bank and shown in Table 7.

161. Based on this analysis it is concluded that relative density, overburden pressure, OCR, and SPT N-value are interrelated for a given sand. This suggests that site-dependent correlations can be developed between these variables where the cohesionless material is of one geologic deposition and grain size distribution. Figure 37 is a plot of Equation 1, using an OCR of 1, superimposed on the data spread of Figure 36. The data points have been omitted for clarity. It should be noted that the data spread in Figure 37 includes data for both normally consolidated and overconsolidated samples, and the Equation 1 curves are for $OCR = 1$ only. The $OCR \neq 1$ data expand the upper band of the 80-psi data and thus the Equation 1 curve appears unconservative at first glance. The Equation 1 curves fit the 40- and 80-psi data reasonably well; however, the 10-psi curve is biased by the higher pressure data and, therefore, Equation 1 is a poor representation of the 10-psi data.

162. A family of best fit curves based on engineering judgment was also prepared, Figure 38. These curves represent the average of data points at their respective testing pressures. A comparison of Figures 37 and 38 shows close agreement between the 40- and 80-psi curves.

Comparisons with Previous Work

Gibbs and Holtz correlation curves

163. The study by Gibbs and Holtz[6] resulted in a recommended family of curves. These recommended curves are superimposed on the WES data spreads in Figure 39. Good agreement exists for the 10-psi testing pressure. The Gibbs and Holtz curves were obtained by testing a coarse to fine sand (Platte River sand) with a mean grain diameter of 1.8 mm. This comparison indicates that grain size distribution exhibits significant influence on the outcome of the SPT, which is in

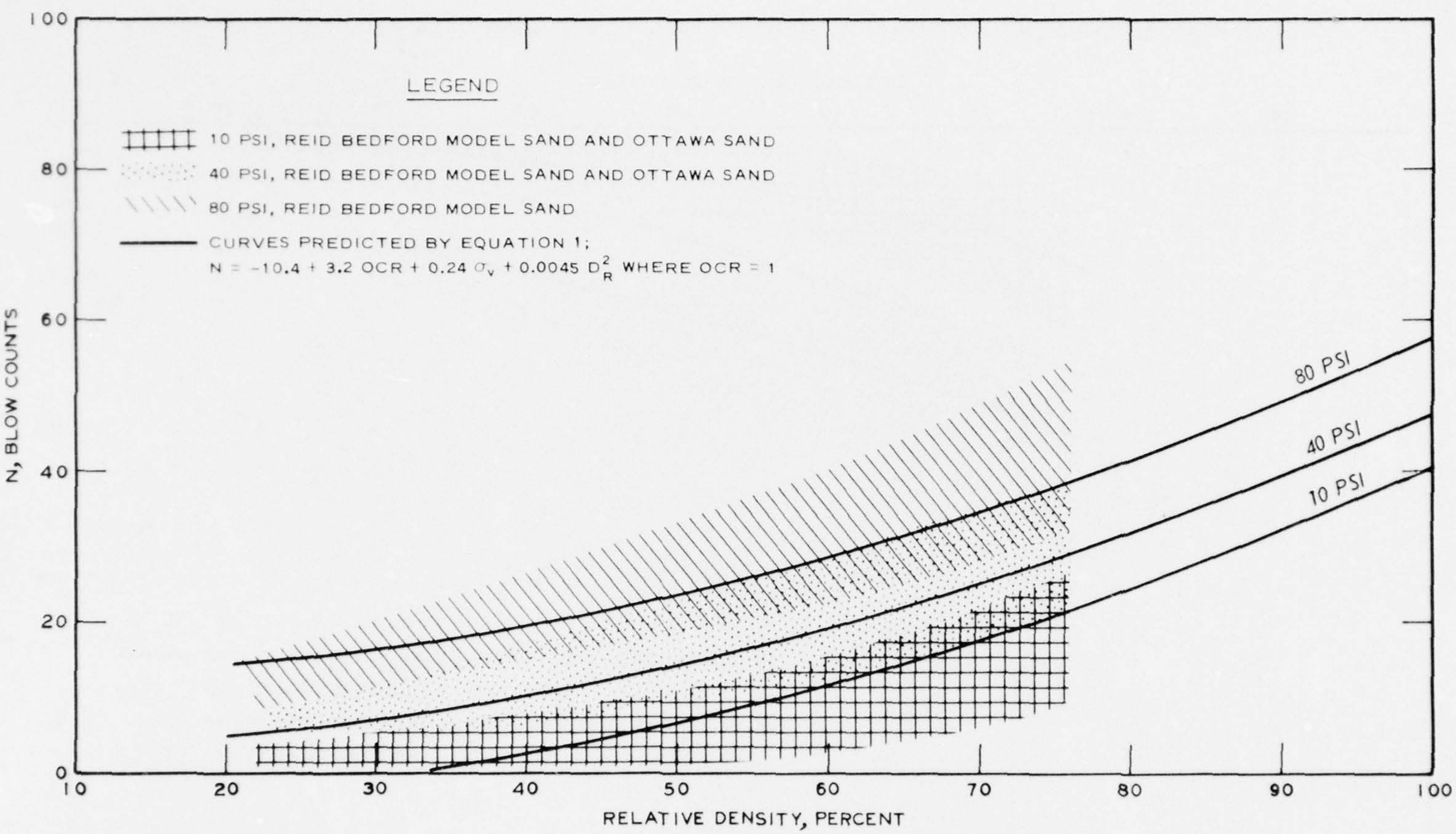

Figure 37. WES data with curves predicted by Equation 1 superimposed

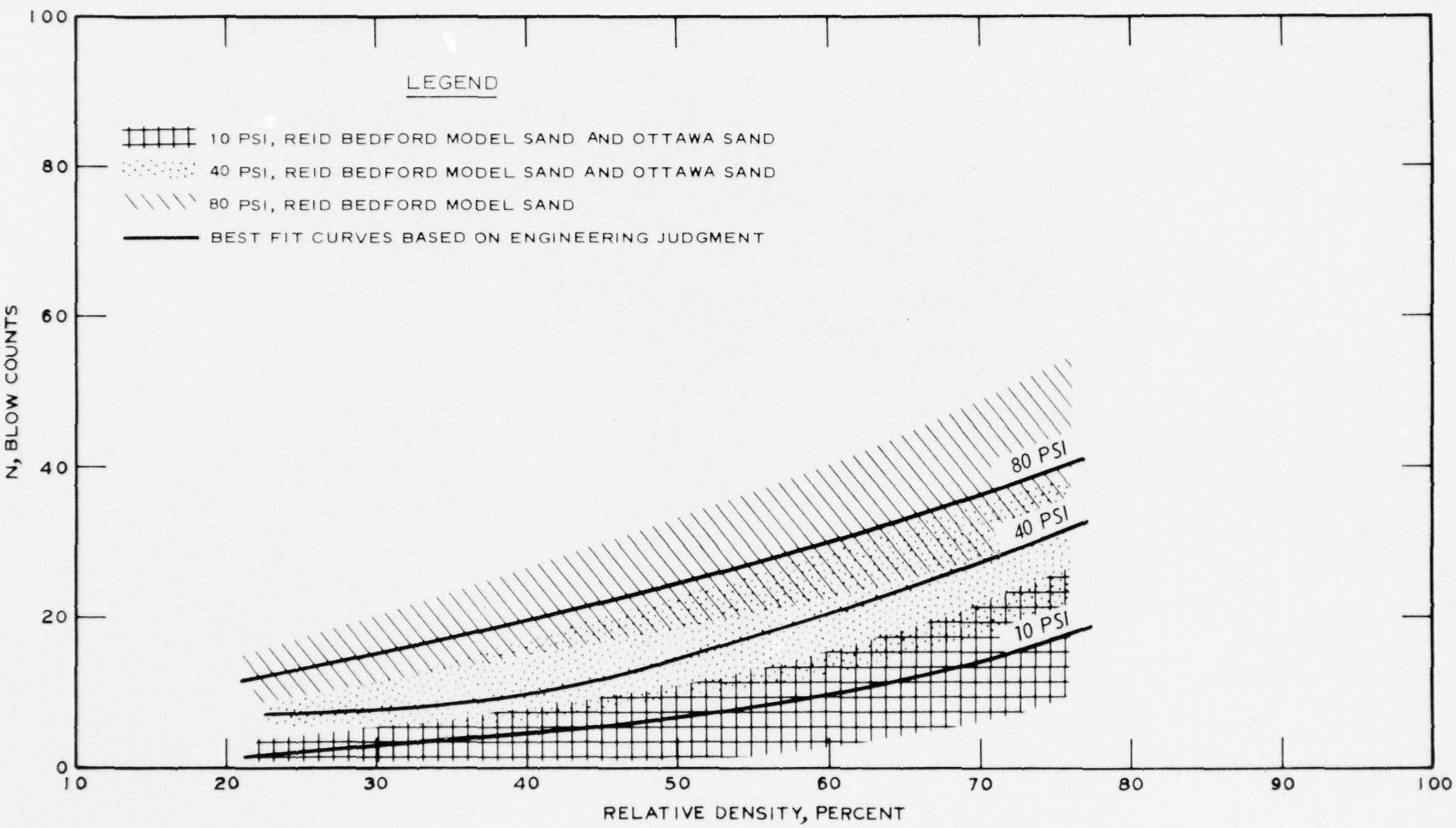

Figure 38. WES data with best fit curves based on engineering judgment superimposed

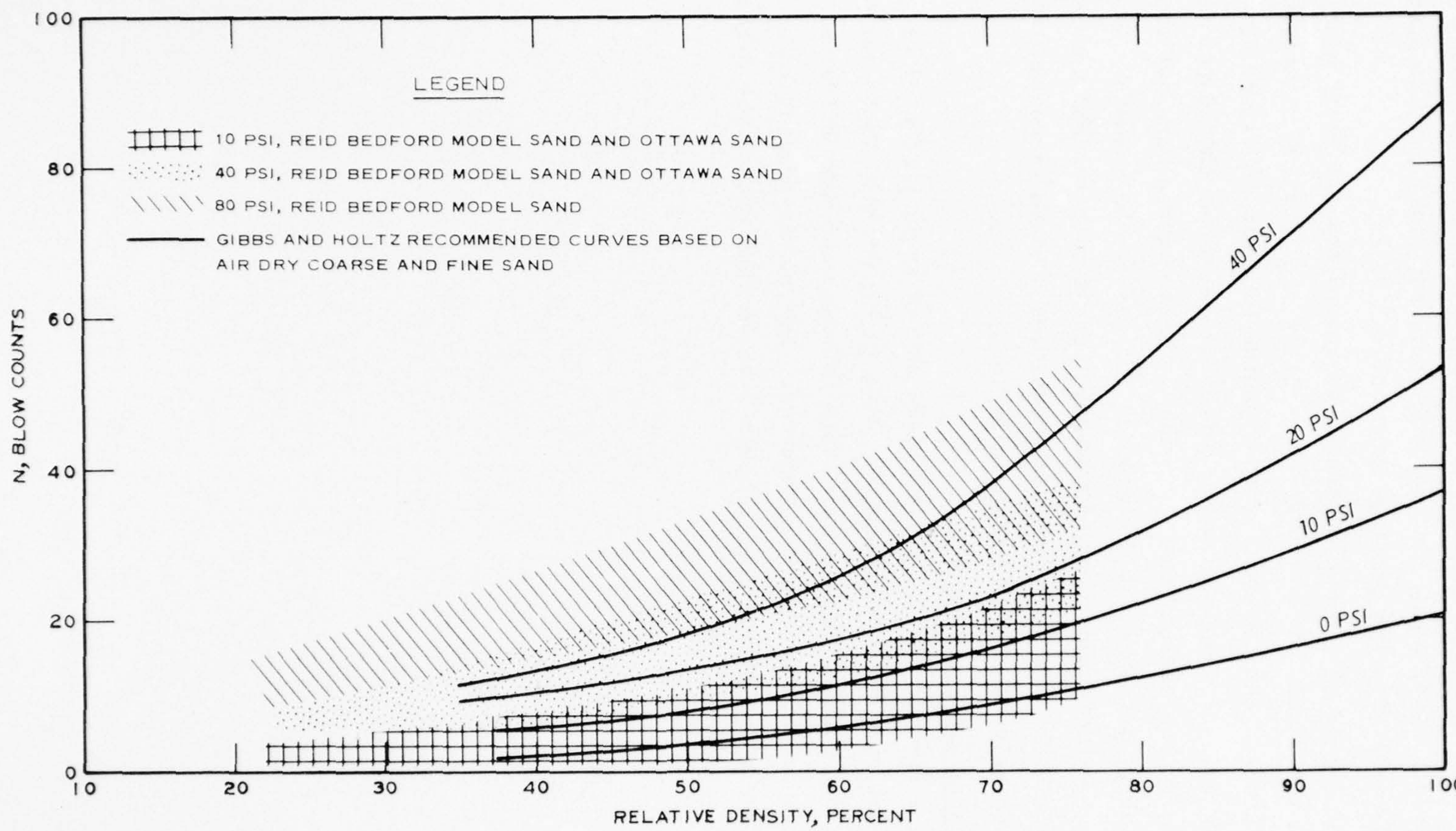

Figure 39. Comparison of WES data and Gibbs and Holtz recommended correlation curves

agreement with the results presented by Kolbuszewski.[12] WES has extended the SPT study using Platte River sand, and early results agree reasonably well with the findings of Gibbs and Holtz.

164. Along with the recommended curves, Gibbs and Holtz also published the family of curves which resulted from testing submerged sands. These curves are superimposed on the WES data in Figure 40. In this instance, there appears to be better agreement at the 40-psi testing pressure, but overall poor agreement. These curves were not considered reliable, and were not recommended for use by the authors. In comparing the Gibbs and Holtz recommended curves with the WES curves, certain variations in equipment and techniques need to be recognized, and for convenience are presented in Table 13.

Bazaraa correlation curves

165. The correlation curves based on the study performed by Bazaraa[7] are superimposed on the WES data in Figure 41. These curves are based on actual field data and take into account many different types of sands derived from many sources. The curves predict lower values of relative density for a given N-value than either the Gibbs and Holtz or WES curves.

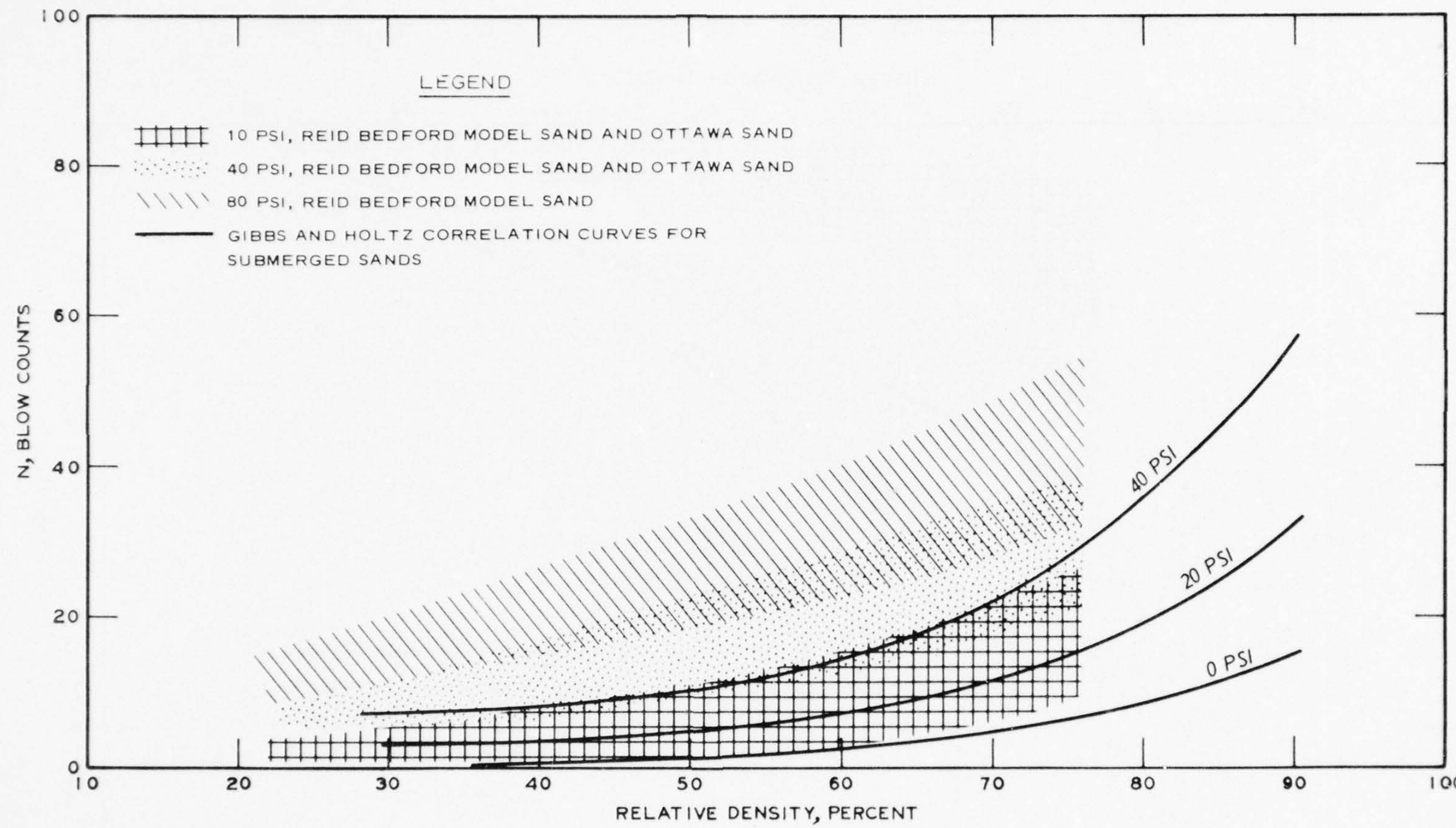

Figure 40. Comparison of WES data and Gibbs and Holtz correlation curves for submerged sands

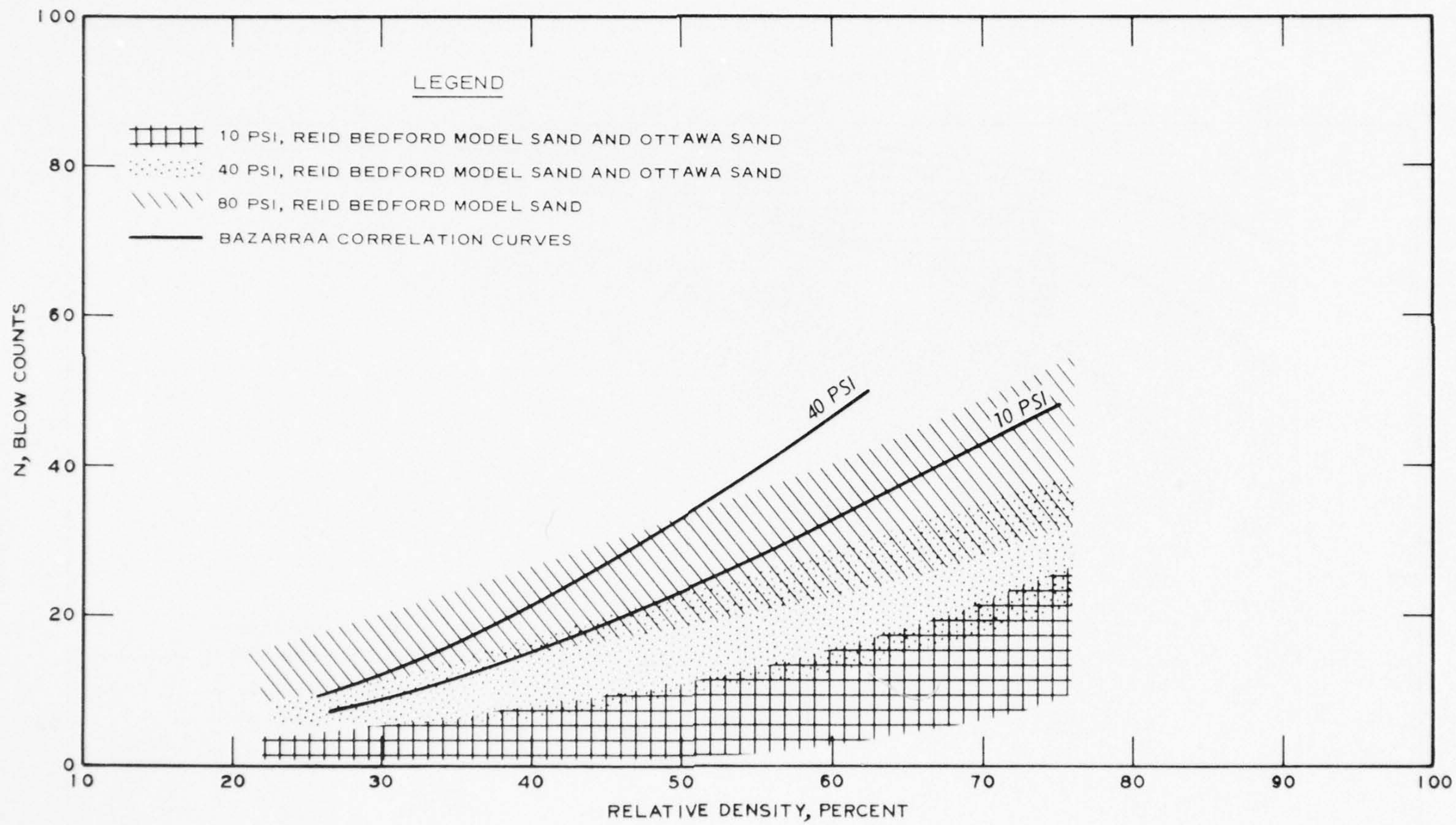

Figure 41. Comparison of WES data and Bazaraa correlation curves

PART VII: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

166. The conclusions drawn from this study apply directly to only the two sands tested. The equations and data presented herein are not intended for use in predicting the penetration resistance or relative density of sands in general, but are presented to describe the empirical behavior of these two sands under the laboratory testing conditions.

- a. The penetration resistance (N-value) was observed to be sensitive to changes in density, overburden pressure, and OCR.
- b. The SPT as performed was fairly repeatable in a nearly homogeneous deposit; however, variations in the testing medium produced scattered N-values. The results obtained do not permit more than a gross estimate of relative density from N-values. A single value of penetration resistance for certain overburden pressures can represent a 30 percent spread (± 15 percent) in relative density (see Figure 36). The heterogeneous conditions of the field would seem to make the task of estimating relative density more difficult; hence, correlations between N-values and relative density should be used cautiously and mainly in a qualitative manner.
- c. It has been recently established that different structures and different lateral stresses are associated with various sand placement techniques.[41] The results of this testing program showed that the penetration resistance was sensitive to the various placement techniques. It is concluded from this that the results reflect variations in the structure and lateral stress conditions of a deposit. In practice, this sensitivity would tend to obscure the actual density condition.[43]
- d. In Figure 36, the tests performed on specimens having an OCR of 3 produced N-values which consistently fell near the top of the scatter band for their respective pressures. This again indicates that the SPT is sensitive to the lateral stress conditions.
- e. Multiple regression analyses were conducted and relationships, in terms of the standard penetration N-value and relative density, were developed. These relationships appear quite good from a statistical point of view, having a coefficient of correlation, r, of approximately 0.9. The relationship for relative density as a

function of N, $\overline{\sigma}_v$, and OCR (Equation 5) has a standard deviation of about ± 7 percent. Caution should be exercised in the use of this equation to predict relative density because it was developed from a limited data bank and applies directly to Reid Bedford Model sand.

f. Based on a comparison between the correlations presented by Bazaraa, Gibbs and Holtz, and WES, it is concluded that the SPT is not sufficiently accurate to be recommended for final evaluation of the density or relative density at a site, unless site-specific correlations are developed. However, the SPT does have value in planning the undisturbed sampling phase of the subsurface investigation and in comparing different sites.

Recommendations

167. Based upon observations made during this study it appears that several areas require further research to permit better understanding of the relationship between the penetration resistance and relative density of cohesionless material.

a. Correlations between SPT N-values and other soil parameters should be obtained on cohesionless materials of various grain size distributions and at other overconsolidation ratios.

b. More research is required to gain insight into the effects of lateral stresses and soil structure on the SPT.

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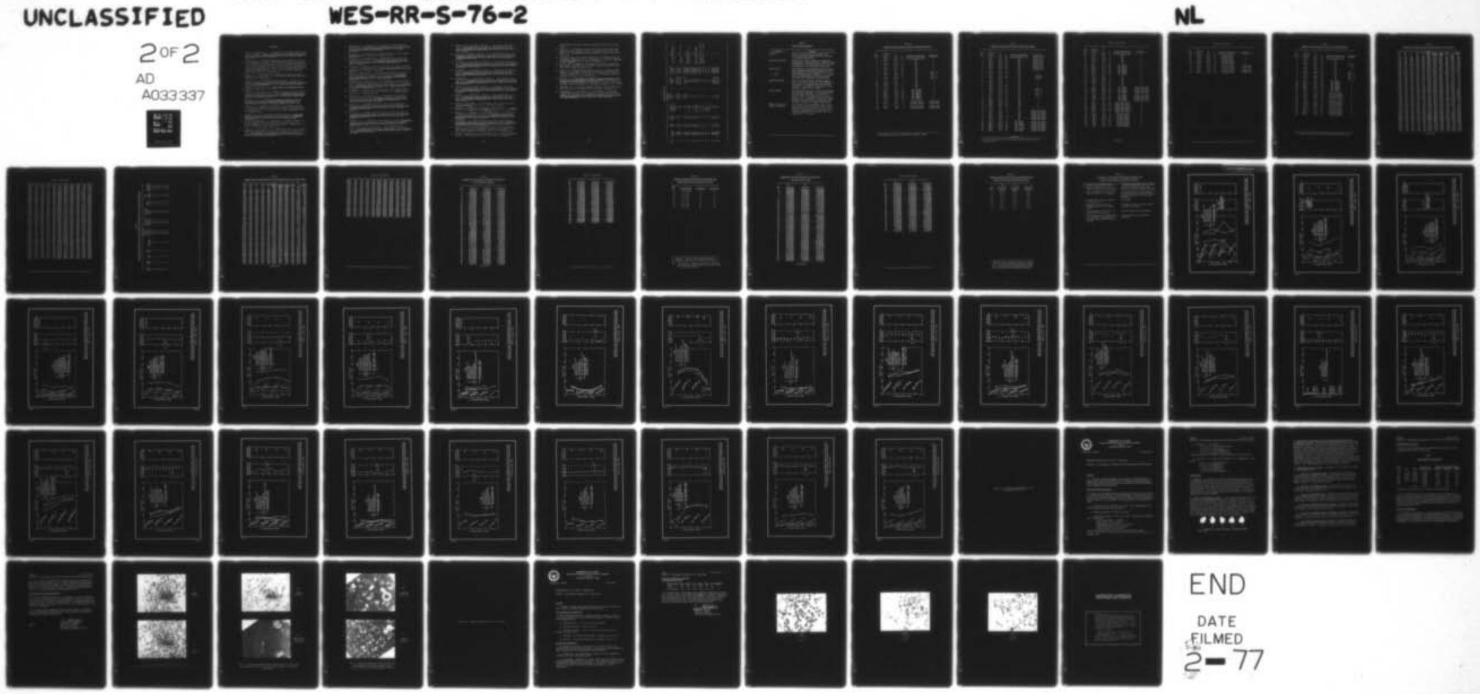

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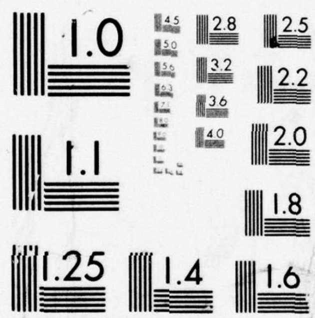

MICROCOPY RESOLUTION TEST CHART
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Table 1

Summary Table of Tests

Test No.	Material	γ_d Placed pcf	D_R Placed percent	Preparation Method	Overburden Pressure Sequence psi	OCR	Undisturbed Sample	Water Table Condition	Remarks
1	RBMS	95.4	40.9	Rotating Rainer (RR)	40	1	None	Submerged	Data considered unreliable
2	RBMS	95.4	40.9	RR	10-40-80	1	Center hole	Submerged	--
3	RBMS	94.4	35.1	RR	5-40-80	1	Center hole	Drained	--
4	RBMS	91.6	18.3	RR	10-40-80	1	Center hole	Submerged	--
5	RBMS	98.5	57.6	RR	10-40	1	Center hole	Submerged	No data at 80 psi; water bag ruptured
6	RBMS	97.7	53.4	RR	10-40-80	3	Center hole	Submerged	--
7	RBMS	94.4	35.2	RR	10-40-80	3	Center hole	Submerged	--
8	RBMS	95.5	41.3	RR	40	1	None	Submerged	Check test for test 1
9	RBMS	93.[illegible]	28.9	RR	40	1	None	Submerged	Rained into water
10	RBMS	99.9	65.1	RR, Rodded	40	1	None	Submerged	Rained into water; rodded
11	RBMS	93.2	28.2	RR	40	1	None	Submerged	--
12	RBMS	100.9	70.5	RR	40	1	None	Submerged	--
13	RBMS	96.0	44.3	RR	40	1	None	Submerged	--
14	RBMS	100.4	67.7	RR, Rodded	40	1	None	Submerged	Rained into water; rodded
15	RBMS	98.9	60.2	RR, Rodded	40	1	None	Submerged	Rained into water; rodded
16	RBMS	92.2	21.9	RR	10	1	None	Submerged	--
17	RBMS	101.4	72.8	RR, Tamped	10	1	None	Submerged	Manual tamping with 1-ft-square plate
18	RBMS	101.5	73.5	RR, Tamped	80	1	None	Submerged	Manual tamping with 1-ft-square plate
19	RBMS	101.3	72.5	Single-Hose Rainer	40	1	None	Submerged	--
20	RBMS	95.4	40.8	Circular Rainer (CR)	40	1	None	Submerged	--
21	RBMS	93.7	30.8	CR	40	1	None	Submerged	--
22	RBMS	97.7	49.7	CR	80	1	Center hole	Submerged	--
23	RBMS	90.5	11.6	CR	80	1	Center hole	Submerged	--
24	RBMS	101.5	73.3	CR	80	1	Center hole	Submerged	--
25	Ottawa	100.9	53.1	CR	10-40	1	Center hole	Submerged	--
26	Ottawa	101.5	56.8	CR	10-40	1	Center hole	Submerged	--

Table 2

List of Test Variables

Variable	Remarks
Density	Density varied along the horizontal and vertical profiles, depending upon the method of specimen preparation.
Overburden Pressure	Control was closely guarded and considered satisfactory. The reduction of vertical stress with depth is considered small due to the compressibility of the stacked-ring facility.
Stress Ratio $k = \frac{\sigma_H}{\sigma_v}$	This stress ratio is dependent upon the placement technique, additional compactive effort, and proximity to the container wall. It is unknown quantitatively; however, it is certain that the magnitude of the lateral stress influences the resistance to penetration.
Sampling Sequence	Due to the small distance between sampling holes, it is very likely that the condition of the specimen is changed with each drilling operation. The amount of disturbance to the original condition is not known.
Stage Testing	This procedure was used to obtain the maximum data from each specimen. It is possible that this procedure affected the results to a greater extent than sampling at one pressure. The fact that the program included both stage testing and one-pressure testing makes stage testing a variable of unknown significance.
Radial Position and Depth in Chamber	The proximity of the peripheral hole to the soil container may facilitate greater lateral stresses on the ring wall side of the hole. Shear and compression waves reflected off the specimen boundaries may interfere with the penetration of the spoon.

Table 3

Summary of Data Points at 10-psi Overburden Pressure

Test No.	γ_d Corrected pcf	D_R %	N	Specimen Preparation	Remarks*
2	95.9	43.8	6	Rotating Rainer (RR)	--
2	95.9	43.8	9	RR	--
4	92.6	24.3	3	RR	--
4	92.6	24.3	3	RR	--
5	98.7	59.7	13	RR	--
5	98.7	59.7	11	RR	--
6	98.2	56.3	12	RR	OCR = 3
6	98.2	56.3	12	RR	OCR = 3
7	94.9	38.0	5	RR	OCR = 3
7	94.9	38.0	4	RR	OCR = 3
16	93.0	27.1	1	RR	--
16	93.0	27.1	1	RR	--
16	93.0	27.1	1	RR	--
16	93.0	27.1	1	RR	--
17	101.5	73.2	17	RR, Tamped	--
17	101.5	73.2	24	RR, Tamped	--
17	101.5	73.2	15	RR, Tamped	--
17	101.5	73.2	19	RR, Tamped	--
17	101.5	73.2	15	RR, Tamped	--
17	101.5	73.2	19	RR, Tamped	--
25	101.4	56.1	3	Circular Rainer	Ottawa Sand
25	101.4	56.1	4	Circular Rainer	Ottawa Sand
26	102.0	59.8	5	Circular Rainer	Ottawa Sand
26	102.0	59.8	6	Circular Rainer	Ottawa Sand

* Reid Bedford sand used except where otherwise stated.

Table 4

Summary of Data Points at 40-psi Overburden Pressure

Test No.	γ_d Corrected pcf	D_R %	N	Specimen Preparation	Remarks*
1	96.2	45.4	25	Rotating Rainer (RR)	Initial Test
1	96.2	45.4	31	RR	Initial Test
1	96.2	45.4	50	RR	Initial Test
1	96.2	45.4	44	RR	Initial Test
1	96.2	45.4	34	RR	Initial Test
1	96.2	45.4	33	RR	Initial Test
1	96.2	45.4	43	RR	Initial Test
1	96.2	45.4	61	RR	Initial Test
2	96.2	45.3	15	RR	--
2	96.2	45.3	20	RR	--
3	95.4	40.9	15	RR	Drained
3	95.4	40.9	12	RR	Drained
4	93.2	27.8	6	RR	--
4	93.2	27.8	9	RR	--
5	98.8	59.7	23	RR	--
5	98.8	59.7	22	RR	--
6	98.4	57.3	25	RR	OCR = 3
6	98.4	57.3	27	RR	OCR = 3
7	95.2	39.7	16	RR	OCR = 3
7	95.2	39.7	16	RR	OCR = 3
8	96.3	45.7	9	RR	--
8	96.3	45.7	12	RR	--
8	96.3	45.7	13	RR	--
8	96.3	45.7	12	RR	--
8	96.3	45.7	13	RR	--
8	96.3	45.7	14	RR	--
8	96.3	45.7	17	RR	--
9	94.1	33.4	6	RR	Rained into Water
9	94.1	33.4	6	RR	Rained into Water
9	94.1	33.4	7	RR	Rained into Water
9	94.1	33.4	6	RR	Rained into Water
9	94.1	33.4	7	RR	Rained into Water
9	94.1	33.4	7	RR	Rained into Water
10	100.0	65.8	41	RR, Rodded	Rained into Water
10	100.0	65.8	38	RR, Rodded	Rained into Water
10	100.0	65.8	38	RR, Rodded	Rained into Water
10	100.0	65.8	32	RR, Rodded	Rained into Water
10	100.0	65.8	41	RR, Rodded	Rained into Water
10	100.0	65.8	39	RR, Rodded	Rained into Water

(Continued)

* All tests were conducted with Reid Bedford Model sand except where otherwise stated.

Table 4 (Continued)

Test No.	γ_d Corrected pcf	D_R %	N	Specimen Preparation	Remarks
11	94.4	35.1	5	Rotating Rainer (RR)	--
11	94.4	35.1	7	RR	--
11	94.4	35.1	7	RR	--
11	94.4	35.1	9	RR	--
11	94.4	35.1	8	RR	--
11	94.4	35.1	8	RR	--
12	101.1	71.5	35	RR, Tamped	--
12	101.1	71.5	32	RR, Tamped	--
12	101.1	71.5	27	RR, Tamped	--
12	101.1	71.5	31	RR, Tamped	--
12	101.1	71.5	30	RR, Tamped	--
12	101.1	71.5	32	RR, Tamped	--
13	96.7	48.2	8	RR	--
13	96.7	48.2	8	RR	--
13	96.7	48.2	9	RR	--
13	96.7	48.2	9	RR	--
13	96.7	48.2	12	RR	--
13	96.7	48.2	11	RR	--
14	100.6	68.8	34	RR, Tamped	Rained into Water
14	100.6	68.8	32	RR, Tamped	Rained into Water
14	100.6	68.8	29	RR, Tamped	Rained into Water
14	100.6	68.8	37	RR, Tamped	Rained into Water
15	99.5	63.2	25	RR, Tamped	Rained into Water
15	99.5	63.2	25	RR, Tamped	Rained into Water
15	99.5	63.2	27	RR, Tamped	Rained into Water
15	99.5	63.2	30	RR, Tamped	Rained into Water
19	101.5	73.5	20	Single Hose Rainer	--
19	101.5	73.5	23	Single Hose Rainer	--
19	101.5	73.5	27	Single Hose Rainer	--
19	101.5	73.5	24	Single Hose Rainer	--
19	101.5	73.5	26	Single Hose Rainer	--
19	101.5	73.5	26	Single Hose Rainer	--
20	96.2	45.3	8	Circular Rainer	--
20	96.2	45.3	9	Circular Rainer	--
20	96.2	45.3	13	Circular Rainer	--
20	96.2	45.3	10	Circular Rainer	--
20	96.2	45.3	12	Circular Rainer	--
20	96.2	45.3	15	Circular Rainer	--
20	96.2	45.3	13	Circular Rainer	--
20	96.2	45.3	12	Circular Rainer	--

(Continued)

Table 4 (Concluded)

Test No.	γ_d Corrected pcf	D_R %	N	Specimen Preparation	Remarks
21	94.8	37.6	8	Circular Rainer	--
21	94.8	37.6	11	Circular Rainer	--
21	94.8	37.6	8	Circular Rainer	--
21	94.8	37.6	9	Circular Rainer	--
21	94.8	37.6	9	Circular Rainer	--
21	94.8	37.6	11	Circular Rainer	--
25	101.9	59.2	16	Circular Rainer	Ottawa Sand
25	101.9	59.2	18	Circular Rainer	Ottawa Sand
26	102.5	62.8	17	Circular Rainer	Ottawa Sand
26	102.5	62.8	21	Circular Rainer	Ottawa Sand

Table 5

Summary of Data Points at 80-psi Overburden Pressure

Test No.	γ_d Corrected pcf	D_R %	N	Specimen Preparation	Remarks*
2	96.3	46.1	25	Rotating Rainer (RR)	--
2	96.3	46.1	31	RR	--
3	95.5	41.4	23	RR	--
3	95.5	41.4	19	RR	Drained
4	93.4	29.5	14	RR	--
4	93.4	29.5	16	RR	--
6	98.7	59.0	35	RR	OCR = 3
6	98.7	59.0	38	RR	OCR = 3
7	95.4	40.9	27	RR	OCR = 3
7	95.4	40.9	30	RR	OCR = 3
18	101.7	74.4	33	RR, Tamped	--
18	101.7	74.4	42	RR, Tamped	--
18	101.7	74.4	39	RR, Tamped	--
18	101.7	74.4	45	RR, Tamped	--
18	101.7	74.4	46	RR, Tamped	--
18	101.7	74.4	49	RR, Tamped	--
22	97.7	53.8	20	Circular Rainer	--
22	97.7	53.8	22	Circular Rainer	--
22	97.7	53.8	20	Circular Rainer	--
22	97.7	53.8	20	Circular Rainer	--
23	92.6	24.3	10	Circular Rainer	--
23	92.6	24.3	9	Circular Rainer	--
23	92.6	24.3	11	Circular Rainer	--
23	92.6	24.3	10	Circular Rainer	--
24	101.7	74.3	32	Circular Rainer	--
24	101.7	74.3	33	Circular Rainer	--
24	101.7	74.3	31	Circular Rainer	--
24	101.7	74.3	34	Circular Rainer	--

* All these tests were performed with Reid Bedford Model sand.

Table 6

Tabulation of Data for Reid Bedford Model and Ottawa Sands

TEST NO.	SAND TYPE	OCR	HOLE NO.	SEQUENCE	CORRECTED DRY DENSITY (PCF)	RELATIVE DENSITY (PERCENT)	VERTICAL STRESS (PSI)	DEPTH (FEET)	SPT N VALUE	RECOVERY (PERCENT)
1.00	1.00	1.00	4.00	1.00	96.20	45.40	40.00	2.50	29.00	1.00
1.00	1.00	1.00	4.00	1.00	96.20	45.40	40.00	4.00	31.00	1.00
1.00	1.00	1.00	1.00	2.00	96.20	45.40	40.00	2.50	50.00	1.00
1.00	1.00	1.00	1.00	2.00	96.20	45.40	40.00	4.00	44.00	1.00
1.00	1.00	1.00	2.00	3.00	96.20	45.40	40.00	2.50	34.00	1.00
1.00	1.00	1.00	2.00	3.00	96.20	45.40	40.00	4.00	33.00	1.00
1.00	1.00	1.00	3.00	4.00	96.20	45.40	40.00	2.50	43.00	1.00
1.00	1.00	1.00	3.00	4.00	96.20	45.40	40.00	4.00	61.00	1.00
2.00	1.00	1.00	3.00	2.00	95.90	43.80	10.00	2.50	6.00	63.30
2.00	1.00	1.00	3.00	2.00	95.90	43.80	10.00	4.00	9.00	66.70
2.00	1.00	1.00	2.00	3.00	96.20	45.30	40.00	2.50	15.00	73.30
2.00	1.00	1.00	2.00	3.00	96.20	45.30	40.00	4.00	20.00	73.30
2.00	1.00	1.00	1.00	4.00	96.30	46.10	80.00	2.50	25.00	66.70
2.00	1.00	1.00	1.00	4.00	96.30	46.10	80.00	4.00	31.00	66.70
3.00	1.00	1.00	1.00	2.00	94.70	36.90	5.00	2.50	4.00	1.00
3.00	1.00	1.00	1.00	2.00	94.70	36.90	5.00	4.00	4.00	1.00
3.00	1.00	1.00	2.00	3.00	95.40	40.90	40.00	2.50	15.00	1.00
3.00	1.00	1.00	2.00	3.00	95.40	40.90	40.00	4.00	12.00	1.00
3.00	1.00	1.00	3.00	4.00	95.50	41.40	80.00	2.50	23.00	1.00
3.00	1.00	1.00	3.00	4.00	95.50	41.40	80.00	4.00	19.00	1.00
4.00	1.00	1.00	2.00	2.00	92.60	24.30	10.00	2.50	3.00	1.00
4.00	1.00	1.00	2.00	2.00	92.60	24.30	10.00	4.00	3.00	1.00
4.00	1.00	1.00	1.00	3.00	93.20	27.80	40.00	2.50	6.00	1.00
4.00	1.00	1.00	3.00	4.00	93.40	29.50	80.00	2.50	14.00	1.00
4.00	1.00	1.00	1.00	3.00	93.20	27.80	40.00	4.00	9.00	1.00
4.00	1.00	1.00	3.00	4.00	93.40	29.50	80.00	4.00	16.00	1.00
5.00	1.00	1.00	2.00	2.00	98.70	59.00	10.00	4.00	11.00	1.00
5.00	1.00	1.00	3.00	3.00	98.80	59.70	40.00	2.50	23.00	1.00
5.00	1.00	1.00	3.00	3.00	98.80	59.70	40.00	4.00	22.00	1.00
6.00	1.00	3.00	2.00	2.00	98.20	56.30	10.00	2.50	12.00	1.00
6.00	1.00	3.00	2.00	2.00	98.20	56.30	10.00	4.00	12.00	1.00
6.00	1.00	3.00	3.00	3.00	98.40	57.30	40.00	2.50	25.00	84.00
6.00	1.00	3.00	3.00	3.00	98.40	57.30	40.00	4.00	27.00	88.00
6.00	1.00	3.00	1.00	4.00	98.70	59.00	80.00	2.50	35.00	88.00
6.00	1.00	3.00	1.00	4.00	98.70	59.00	80.00	4.00	38.00	88.00
7.00	1.00	3.00	1.00	2.00	94.90	38.00	10.00	2.50	5.00	88.00
7.00	1.00	3.00	1.00	2.00	94.90	38.00	10.00	4.00	4.00	84.00
7.00	1.00	3.00	2.00	3.00	95.20	39.70	40.00	4.00	16.00	84.00
7.00	1.00	3.00	3.00	4.00	95.40	40.90	80.00	2.50	27.00	92.00
7.00	1.00	3.00	3.00	4.00	95.40	40.90	80.00	4.00	30.00	88.00
8.00	1.00	1.00	1.00	2.00	96.30	45.70	40.00	2.50	12.00	1.00
8.00	1.00	1.00	1.00	2.00	96.30	45.70	40.00	4.00	13.00	1.00
8.00	1.00	1.00	2.00	3.00	96.30	45.70	40.00	2.50	12.00	1.00
8.00	1.00	1.00	2.00	3.00	96.30	45.70	40.00	4.00	13.00	1.00
8.00	1.00	1.00	3.00	4.00	96.30	45.70	40.00	2.50	14.00	1.00
8.00	1.00	1.00	3.00	4.00	96.30	45.70	40.00	4.00	17.00	1.00
9.00	1.00	1.00	4.00	1.00	94.10	33.40	40.00	2.50	6.00	56.80
9.00	1.00	1.00	4.00	1.00	94.10	33.40	40.00	4.00	6.00	88.80
9.00	1.00	1.00	1.00	2.00	94.10	33.40	40.00	2.50	7.00	48.80
9.00	1.00	1.00	1.00	2.00	94.10	33.40	40.00	4.00	6.00	40.80
9.00	1.00	1.00	2.00	3.00	94.10	33.40	40.00	2.50	7.00	48.80
9.00	1.00	1.00	2.00	3.00	94.10	33.40	40.00	4.00	7.00	72.80
10.00	1.00	1.00	4.00	1.00	100.00	65.80	40.00	2.50	41.00	68.00
10.00	1.00	1.00	4.00	1.00	100.00	65.80	40.00	4.00	38.00	78.40
10.00	1.00	1.00	1.00	2.00	100.00	65.80	40.00	2.50	38.00	81.60
10.00	1.00	1.00	1.00	2.00	100.00	65.80	40.00	4.00	32.00	72.00
10.00	1.00	1.00	2.00	3.00	100.00	65.80	40.00	2.50	41.00	84.00
10.00	1.00	1.00	2.00	3.00	100.00	65.80	40.00	4.00	39.00	84.00
11.00	1.00	1.00	4.00	1.00	94.40	35.10	40.00	2.50	5.00	92.00
11.00	1.00	1.00	4.00	1.00	94.40	35.10	40.00	4.00	7.00	88.00
11.00	1.00	1.00	1.00	2.00	94.40	35.10	40.00	2.50	7.00	68.00
11.00	1.00	1.00	1.00	2.00	94.40	35.10	40.00	4.00	9.00	87.20
11.00	1.00	1.00	2.00	3.00	94.40	35.10	40.00	2.50	8.00	90.40
12.00	1.00	1.00	4.00	1.00	101.10	71.50	40.00	2.50	35.00	84.00
12.00	1.00	1.00	4.00	1.00	101.10	71.50	40.00	4.00	32.00	72.00
12.00	1.00	1.00	1.00	2.00	101.10	71.50	40.00	2.50	27.00	72.00
12.00	1.00	1.00	1.00	2.00	101.10	71.50	40.00	4.00	31.00	72.00
12.00	1.00	1.00	2.00	3.00	101.10	71.50	40.00	2.50	30.00	76.00
12.00	1.00	1.00	2.00	3.00	101.10	71.50	40.00	4.00	32.00	80.00

(Continued)

Table 6 (Concluded)

13.00	1.00	1.00	4.00	1.00	96.70	48.20	40.00	2.50	8.00	76.00
13.00	1.00	1.00	4.00	1.00	96.70	48.20	40.00	4.00	8.00	70.40
13.00	1.00	1.00	1.00	2.00	96.70	48.20	40.00	2.50	9.00	72.00
13.00	1.00	1.00	1.00	2.00	96.70	48.20	40.00	4.00	9.00	72.00
13.00	1.00	1.00	2.00	3.00	96.70	48.20	40.00	2.50	12.00	74.40
14.00	1.00	1.00	4.00	1.00	100.60	68.80	40.00	2.50	34.00	77.60
14.00	1.00	1.00	4.00	1.00	100.60	68.80	40.00	4.00	32.00	77.60
14.00	1.00	1.00	1.00	2.00	100.60	68.80	40.00	2.50	29.00	70.40
14.00	1.00	1.00	1.00	2.00	100.60	68.80	40.00	4.00	37.00	76.00
15.00	1.00	1.00	4.00	1.00	99.50	63.20	40.00	2.50	25.00	81.60
15.00	1.00	1.00	4.00	1.00	99.50	63.20	40.00	4.00	25.00	69.60
15.00	1.00	1.00	1.00	2.00	99.50	63.20	40.00	2.50	27.00	77.60
15.00	1.00	1.00	1.00	2.00	99.50	63.20	40.00	4.00	30.00	80.00
16.00	1.00	1.00	4.00	1.00	93.00	27.10	10.00	2.50	1.00	60.00
16.00	1.00	1.00	4.00	1.00	93.00	27.10	10.00	4.00	1.00	60.00
16.00	1.00	1.00	1.00	2.00	93.00	27.10	10.00	2.50	1.00	52.00
16.00	1.00	1.00	1.00	2.00	93.00	27.10	10.00	4.00	1.00	44.00
17.00	1.00	1.00	4.00	1.00	101.50	73.20	10.00	2.50	17.00	78.40
17.00	1.00	1.00	4.00	1.00	101.50	73.20	10.00	4.00	24.00	68.80
17.00	1.00	1.00	1.00	2.00	101.50	73.20	10.00	2.50	15.00	72.00
17.00	1.00	1.00	1.00	2.00	101.50	73.20	10.00	4.00	19.00	70.40
17.00	1.00	1.00	2.00	3.00	101.50	73.20	10.00	2.50	15.00	75.20
17.00	1.00	1.00	2.00	3.00	101.50	73.20	10.00	4.00	19.00	68.80
18.00	1.00	1.00	4.00	1.00	101.70	74.40	80.00	2.50	33.00	67.20
18.00	1.00	1.00	4.00	1.00	101.70	74.40	80.00	4.00	42.00	72.80
18.00	1.00	1.00	1.00	2.00	101.70	74.40	80.00	2.50	39.00	80.80
18.00	1.00	1.00	1.00	2.00	101.70	74.40	80.00	4.00	45.00	79.20
18.00	1.00	1.00	2.00	3.00	101.70	74.40	80.00	4.00	49.00	83.20
19.00	1.00	1.00	4.00	1.00	101.50	73.50	40.00	2.50	20.00	78.40
19.00	1.00	1.00	4.00	1.00	101.50	73.50	40.00	4.00	23.00	80.00
19.00	1.00	1.00	1.00	2.00	101.50	73.50	40.00	2.50	27.00	75.20
19.00	1.00	1.00	1.00	2.00	101.50	73.50	40.00	4.00	24.00	76.00
19.00	1.00	1.00	2.00	3.00	101.50	73.50	40.00	2.50	26.00	68.80
19.00	1.00	1.00	2.00	3.00	101.50	73.50	40.00	4.00	26.00	70.40
20.00	1.00	1.00	4.00	1.00	96.20	45.30	40.00	4.00	9.00	79.20
20.00	1.00	1.00	1.00	2.00	96.20	45.30	40.00	2.50	13.00	71.20
20.00	1.00	1.00	1.00	2.00	96.20	45.30	40.00	4.00	10.00	65.60
20.00	1.00	1.00	3.00	3.00	96.20	45.30	40.00	2.50	12.00	74.40
20.00	1.00	1.00	3.00	3.00	96.20	45.30	40.00	4.00	15.00	67.20
20.00	1.00	1.00	2.00	4.00	96.20	45.30	40.00	2.50	13.00	69.60
20.00	1.00	1.00	2.00	4.00	96.20	45.30	40.00	4.00	12.00	66.40
21.00	1.00	1.00	4.00	1.00	94.80	37.60	40.00	2.50	8.00	76.80
21.00	1.00	1.00	4.00	1.00	94.80	37.60	40.00	4.00	11.00	80.80
21.00	1.00	1.00	1.00	2.00	94.80	37.60	40.00	2.50	8.00	72.80
21.00	1.00	1.00	1.00	2.00	94.80	37.60	40.00	4.00	9.00	66.40
21.00	1.00	1.00	2.00	3.00	94.80	37.60	40.00	2.50	9.00	72.80
22.00	1.00	1.00	1.00	2.00	97.70	53.80	80.00	2.50	20.00	79.20
22.00	1.00	1.00	1.00	2.00	97.70	53.80	80.00	4.00	22.00	71.20
22.00	1.00	1.00	2.00	3.00	97.70	53.80	80.00	2.50	20.00	72.80
22.00	1.00	1.00	2.00	3.00	97.70	53.80	80.00	4.00	20.00	70.40
23.00	1.00	1.00	1.00	2.00	92.60	24.30	80.00	2.50	10.00	77.60
23.00	1.00	1.00	1.00	2.00	92.60	24.30	80.00	4.00	9.00	75.20
23.00	1.00	1.00	2.00	3.00	92.60	24.30	80.00	2.50	11.00	78.40
23.00	1.00	1.00	2.00	3.00	92.60	24.30	80.00	4.00	10.00	77.60
24.00	1.00	1.00	1.00	2.00	101.70	74.30	80.00	2.50	32.00	83.20
24.00	1.00	1.00	1.00	2.00	101.70	74.30	80.00	4.00	33.00	81.60
24.00	1.00	1.00	2.00	3.00	101.70	74.30	80.00	2.50	31.00	88.80
24.00	1.00	1.00	2.00	3.00	101.70	74.30	80.00	4.00	34.00	84.00
25.00	2.00	1.00	1.00	2.00	101.40	56.10	10.00	2.50	3.00	56.80
25.00	2.00	1.00	1.00	2.00	101.40	56.10	10.00	4.00	4.00	69.60
25.00	2.00	1.00	2.00	3.00	101.90	59.20	40.00	2.50	16.00	81.60
25.00	2.00	1.00	2.00	3.00	101.90	59.20	40.00	4.00	18.00	71.20
26.00	2.00	1.00	1.00	2.00	102.00	59.80	10.00	2.50	5.00	69.60
26.00	2.00	1.00	1.00	2.00	102.00	59.80	10.00	4.00	6.00	65.60
26.00	2.00	1.00	2.00	3.00	102.50	62.80	40.00	2.50	17.00	76.00
26.00	2.00	1.00	2.00	3.00	102.50	62.80	40.00	4.00	21.00	65.60

Table 7

Random Data Withheld from the Regression Analyses for Verification Purposes

Test No.	Sand Type	OCR	Hole No.	Sequence	Corrected Dry Density pcf	Relative Density percent	Vertical Stress psi	Depth ft	SPT N Value	Recovery percent
5	1	1	2	2	98.7	59.0	10	2.5	13	1.0
11	1	1	2	3	94.4	35.1	40	4.0	8	90.4
13	1	1	2	3	96.7	48.2	40	4.0	11	68.0
20	1	1	4	1	96.2	45.3	40	2.5	8	78.4
21	1	1	2	3	94.8	37.6	40	4.0	11	1.0
18	1	1	2	3	101.7	74.4	80	2.5	46	76.8
7	1	3	2	3	95.2	39.7	40	2.5	16	92.0

Table 8

Tabulation of Selected Data for Reid Bedford Model and Ottawa Sands

TEST NO.	SAND TYPE	OCR	HOLE NO.	SEQUENCE	CORRECTED DRY DENSITY (PCF)	RELATIVE DENSITY (PERCENT)	VERTICAL STRESS (PSI)	DEPTH (FEET)	SPT N VALUE	RECOVERY (PERCENT)
2.00	1.00	1.00	3.00	2.00	95.90	43.80	10.00	2.50	6.00	63.30
2.00	1.00	1.00	3.00	2.00	95.90	43.80	10.00	4.00	9.00	66.70
2.00	1.00	1.00	2.00	3.00	96.20	45.30	40.00	2.50	15.00	73.30
2.00	1.00	1.00	2.00	3.00	96.20	45.30	40.00	4.00	20.00	73.30
2.00	1.00	1.00	1.00	4.00	96.30	46.10	80.00	2.50	25.00	66.70
2.00	1.00	1.00	1.00	4.00	96.30	46.10	80.00	4.00	31.00	66.70
4.00	1.00	1.00	2.00	2.00	92.60	24.30	10.00	2.50	3.00	1.00
4.00	1.00	1.00	2.00	2.00	92.60	24.30	10.00	4.00	3.00	1.00
4.00	1.00	1.00	1.00	3.00	93.20	27.80	40.00	2.50	6.00	1.00
4.00	1.00	1.00	3.00	4.00	93.40	29.50	80.00	2.50	14.00	1.00
4.00	1.00	1.00	1.00	3.00	93.20	27.80	40.00	4.00	9.00	1.00
4.00	1.00	1.00	3.00	4.00	93.40	29.50	80.00	4.00	16.00	1.00
5.00	1.00	1.00	2.00	2.00	98.70	59.00	10.00	4.00	11.00	1.00
5.00	1.00	1.00	3.00	3.00	98.80	59.70	40.00	2.50	23.00	1.00
5.00	1.00	1.00	3.00	3.00	98.80	59.70	40.00	4.00	22.00	1.00
6.00	1.00	3.00	2.00	2.00	98.20	56.30	10.00	2.50	12.00	1.00
6.00	1.00	3.00	2.00	2.00	98.20	56.30	10.00	4.00	12.00	1.00
6.00	1.00	3.00	3.00	3.00	98.40	57.30	40.00	2.50	25.00	84.00
6.00	1.00	3.00	3.00	3.00	98.40	57.30	40.00	4.00	27.00	88.00
6.00	1.00	3.00	1.00	4.00	98.70	59.00	80.00	2.50	35.00	88.00
6.00	1.00	3.00	1.00	4.00	98.70	59.00	80.00	4.00	38.00	88.00
7.00	1.00	3.00	1.00	2.00	94.90	38.00	10.00	2.50	5.00	88.00
7.00	1.00	3.00	1.00	2.00	94.90	38.00	10.00	4.00	4.00	84.00
7.00	1.00	3.00	2.00	3.00	95.20	39.70	40.00	4.00	16.00	84.00
7.00	1.00	3.00	3.00	4.00	95.40	40.90	80.00	2.50	27.00	92.00
7.00	1.00	3.00	3.00	4.00	95.40	40.90	80.00	4.00	30.00	88.00
8.00	1.00	1.00	1.00	2.00	96.30	45.70	40.00	2.50	12.00	1.00
8.00	1.00	1.00	1.00	2.00	96.30	45.70	40.00	4.00	13.00	1.00
8.00	1.00	1.00	2.00	3.00	96.30	45.70	40.00	2.50	12.00	1.00
8.00	1.00	1.00	2.00	3.00	96.30	45.70	40.00	4.00	13.00	1.00
8.00	1.00	1.00	3.00	4.00	96.30	45.70	40.00	2.50	14.00	1.00
8.00	1.00	1.00	3.00	4.00	96.30	45.70	40.00	4.00	17.00	1.00
11.00	1.00	1.00	4.00	1.00	94.40	35.10	40.00	2.50	5.00	92.00
11.00	1.00	1.00	4.00	1.00	94.40	35.10	40.00	4.00	7.00	88.00
11.00	1.00	1.00	1.00	2.00	94.40	35.10	40.00	2.50	7.00	88.00
11.00	1.00	1.00	1.00	2.00	94.40	35.10	40.00	4.00	9.00	87.20
11.00	1.00	1.00	2.00	3.00	94.40	35.10	40.00	2.50	8.00	90.40
12.00	1.00	1.00	4.00	1.00	101.10	71.50	40.00	2.50	35.00	84.00
12.00	1.00	1.00	4.00	1.00	101.10	71.50	40.00	4.00	32.00	72.00
12.00	1.00	1.00	1.00	2.00	101.10	71.50	40.00	2.50	27.00	72.00
12.00	1.00	1.00	1.00	2.00	101.10	71.50	40.00	4.00	31.00	72.00
12.00	1.00	1.00	2.00	3.00	101.10	71.50	40.00	2.50	30.00	76.00
12.00	1.00	1.00	2.00	3.00	101.10	71.50	40.00	4.00	32.00	80.00
13.00	1.00	1.00	4.00	1.00	96.70	48.20	40.00	2.50	8.00	76.00
13.00	1.00	1.00	4.00	1.00	96.70	48.20	40.00	4.00	8.00	70.40
13.00	1.00	1.00	1.00	2.00	96.70	48.20	40.00	2.50	9.00	72.00
13.00	1.00	1.00	1.00	2.00	96.70	48.20	40.00	4.00	9.00	72.00
13.00	1.00	1.00	2.00	3.00	96.70	48.20	40.00	2.50	12.00	74.40
16.00	1.00	1.00	4.00	1.00	93.00	27.10	10.00	2.50	1.00	60.00
16.00	1.00	1.00	4.00	1.00	93.00	27.10	10.00	4.00	1.00	60.00
16.00	1.00	1.00	1.00	2.00	93.00	27.10	10.00	2.50	1.00	52.00
16.00	1.00	1.00	1.00	2.00	93.00	27.10	10.00	4.00	1.00	44.00
17.00	1.00	1.00	4.00	1.00	101.50	73.20	10.00	2.50	17.00	78.40
17.00	1.00	1.00	4.00	1.00	101.50	73.20	10.00	4.00	24.00	68.80
17.00	1.00	1.00	1.00	2.00	101.50	73.20	10.00	2.50	15.00	72.00
17.00	1.00	1.00	1.00	2.00	101.50	73.20	10.00	4.00	19.00	70.40
17.00	1.00	1.00	2.00	3.00	101.50	73.20	10.00	2.50	15.00	75.20
17.00	1.00	1.00	2.00	3.00	101.50	73.20	10.00	4.00	19.00	68.80
18.00	1.00	1.00	4.00	1.00	101.70	74.40	80.00	2.50	33.00	67.20
18.00	1.00	1.00	4.00	1.00	101.70	74.40	80.00	4.00	42.00	72.80
18.00	1.00	1.00	1.00	2.00	101.70	74.40	80.00	2.50	39.00	80.80
18.00	1.00	1.00	1.00	2.00	101.70	74.40	80.00	4.00	45.00	79.20
18.00	1.00	1.00	2.00	3.00	101.70	74.40	80.00	4.00	49.00	83.20
19.00	1.00	1.00	4.00	1.00	101.50	73.50	40.00	2.50	20.00	78.40
19.00	1.00	1.00	4.00	1.00	101.50	73.50	40.00	4.00	23.00	80.00
19.00	1.00	1.00	1.00	2.00	101.50	73.50	40.00	2.50	27.00	75.20
19.00	1.00	1.00	1.00	2.00	101.50	73.50	40.00	4.00	24.00	76.00
19.00	1.00	1.00	2.00	3.00	101.50	73.50	40.00	2.50	26.00	68.80

(Continued)

Table 8 (Concluded)

19.00	1.00	1.00	2.00	3.00	101.50	73.50	40.00	4.00	26.00	70.40
20.00	1.00	1.00	4.00	1.00	96.20	85.30	40.00	4.00	9.00	79.20
20.00	1.00	1.00	1.00	2.00	96.20	85.30	40.00	2.50	13.00	71.20
20.00	1.00	1.00	1.00	2.00	96.20	85.30	40.00	4.00	10.00	65.60
20.00	1.00	1.00	3.00	3.00	96.20	85.30	40.00	2.50	12.00	74.40
20.00	1.00	1.00	3.00	3.00	96.20	85.30	40.00	4.00	15.00	67.20
20.00	1.00	1.00	2.00	4.00	96.20	85.30	40.00	2.50	13.00	69.60
20.00	1.00	1.00	2.00	4.00	96.20	85.30	40.00	4.00	12.00	66.40
21.00	1.00	1.00	4.00	1.00	94.80	37.60	40.00	2.50	8.00	76.80
21.00	1.00	1.00	4.00	1.00	94.80	37.60	40.00	4.00	11.00	80.80
21.00	1.00	1.00	1.00	2.00	94.80	37.60	40.00	2.50	8.00	72.80
21.00	1.00	1.00	1.00	2.00	94.80	37.60	40.00	4.00	9.00	66.40
21.00	1.00	1.00	2.00	3.00	94.80	37.60	40.00	2.50	9.00	72.80
22.00	1.00	1.00	1.00	2.00	97.70	53.80	80.00	2.50	20.00	79.20
22.00	1.00	1.00	1.00	2.00	97.70	53.80	80.00	4.00	22.00	71.20
22.00	1.00	1.00	2.00	3.00	97.70	53.80	80.00	2.50	20.00	72.80
22.00	1.00	1.00	2.00	3.00	97.70	53.80	80.00	4.00	20.00	70.40
23.00	1.00	1.00	1.00	2.00	92.60	24.30	80.00	2.50	10.00	77.60
23.00	1.00	1.00	1.00	2.00	92.60	24.30	80.00	4.00	9.00	75.20
23.00	1.00	1.00	2.00	3.00	92.60	24.30	80.00	2.50	11.00	78.40
23.00	1.00	1.00	2.00	3.00	92.60	24.30	80.00	4.00	10.00	77.60
24.00	1.00	1.00	1.00	2.00	101.70	24.30	80.00	2.50	32.00	83.20
24.00	1.00	1.00	1.00	2.00	101.70	24.30	80.00	4.00	33.00	81.60
24.00	1.00	1.00	2.00	3.00	101.70	24.30	80.00	2.50	31.00	88.80
24.00	1.00	1.00	2.00	3.00	101.70	24.30	80.00	4.00	34.00	84.00
25.00	2.00	1.00	1.00	2.00	101.40	56.10	10.00	2.50	3.00	56.80
25.00	2.00	1.00	1.00	2.00	101.40	56.10	10.00	4.00	4.00	69.60
25.00	2.00	1.00	2.00	3.00	101.90	59.20	40.00	2.50	16.00	81.60
25.00	2.00	1.00	2.00	3.00	101.90	59.20	40.00	4.00	18.00	71.20
26.00	2.00	1.00	1.00	2.00	102.00	59.80	10.00	2.50	5.00	69.60
26.00	2.00	1.00	1.00	2.00	102.00	59.80	10.00	4.00	6.00	65.60
26.00	2.00	1.00	2.00	3.00	102.50	62.80	40.00	2.50	17.00	76.00
26.00	2.00	1.00	2.00	3.00	102.50	62.80	40.00	4.00	21.00	65.60

Table 9

Comparison of N-Values Predicted by Equation 1

With Observed N-Values

Set	N Predicted	N Observed	Difference
1	3,84139600	6.00000000	-2,15860400
2	3,84139600	9.00000000	-5,15860403
3	11,69818282	15.00000000	-3,30181709
4	11,69818282	20,00000000	-8,30181718
5	21,69794702	25.00000000	-3,30205277
6	21,69794702	31.00000000	-9,30205286
7	-2,17344731	3.00000000	-5,17344731
8	-2,17344731	3,00000000	-5,17344731
9	5,90392232	6.00000000	-0,09607764
10	16,01370621	14,00000000	2,01370639
11	5,90392232	9.00000000	-3,09607765
12	16,01370621	16,00000000	0,01370641
13	10,91888631	11.00000000	-0,08111361
14	18,54666567	23.00000000	-4,45333433
15	18.54666567	22.00000000	-3,45333430
16	15,82975781	12,00000000	3,82975781
17	15,82975781	12.00000000	3,82975781
18	23,59572983	25.00000000	-1,40427016
19	23,59572983	27.00000000	-3,40427017
20	34,15981436	35,00000000	-0,84018540
21	34,15981436	38.00000000	-3,84018540
22	8,01338291	5,00000000	3,01338297
23	8,01338291	4.00000000	4,01338297
24	15,86310387	16,00000000	-0,13689607
25	25,96976257	27.00000000	-1.03023723
26	25,96976257	30,00000000	-4,03023726
27	11,86305356	12.00000000	-0,13694634
28	11,86305356	13,00000000	-1,13694635
29	11,86305356	12,00000000	-0.13694634
30	11,86305356	13,00000000	-1,13694635
31	11,86305356	14,00000000	-2,13694635
32	11,86305356	17.00000000	-5,13694638
33	7,98369605	5.00000000	2,98369607
34	7,98369605	7.00000000	0,98369610
35	7.98369605	7.00000000	0.98369610
36	7,98369605	9,00000000	-1,01630391
37	7,98369605	8.00000000	-0,01630390
38	25,55893255	35.00000000	-9,44106746
39	25.55893255	32.00000000	-6,44106740
40	25,55893255	27.00000000	-1,44106738
41	25,55893255	31.00000000	-5,44106740
42	25,55893255	30.00000000	-4,44106740
43	25,55893255	32.00000000	-6,44106740
44	12,92633497	8.00000000	4,92633497
45	12,92633497	8,00000000	4,92633497
46	12,92633497	9.00000000	3.92633497
47	12.92633497	9.00000000	3,92633497
48	12,92633497	12.00000000	0.92633498
49	-1,52157320	1.00000000	-2,52157322
50	-1,52157320	1.00000000	-2.52157322
51	-1,52157320	1.00000000	-2,52157322
52	-1,52157320	1.00000000	-2,52157322
53	19.42169492	17.00000000	2,42169458
54	19,42169492	24.00000000	-4,57830542
55	19,42169492	15.00000000	4.42169458
56	19,42169492	19.00000000	0,42169458
57	19,42169492	15,00000000	4,42169458
58	19,42169492	19.00000000	0,42169458
59	37,14394808	33,00000000	4,14394844
60	37,14394808	42,00000000	-4,85605157
61	37,14394808	39,00000000	-1,85605152
62	37,14394808	45.00000000	-7,85605157
63	37,14394808	49.00000000	-11,85605157
64	26,87246417	20.00000000	6,87246435
65	26,87246417	23.00000000	3,87246439
66	26.87246417	27.00000000	-0,12753559

(Continued)

Table 9 (Concluded)

Set	N Predicted	N Observed	Difference
67	26,87246417	24.00000000	2,87246439
68	26,87246417	26.00000000	0,87246440
69	26,87246417	26.00000000	0,87246440
70	11,69818282	9,00000000	2,69818291
71	11,69818282	13,00000000	-1,30181707
72	11,69818282	10.00000000	1,69818293
73	11,69818282	12.00000000	-0,30181707
74	11,69818282	15,00000000	-3,30181709
75	11,69818282	13,00000000	-1,30181707
76	11,69818282	12,00000000	-0,30181707
77	8,80691815	8.00000000	0,80691817
78	8,80691815	11,00000000	-2,19308183
79	8,80691815	8,00000000	0,80691817
80	8,80691815	9,00000000	-0,19308182
81	8,80691815	9,00000000	-0,19308182
82	25,18211293	20,00000000	5,18211305
83	25,18211293	22.00000000	3,18211308
84	25,18211293	20,00000000	5,18211305
85	25,18211293	20.00000000	5,18211305
86	14,74655580	10,00000000	4,74655587
87	14,74655580	9.00000000	5,74655587
88	14,74655580	11.00000000	3,74655587
89	14,74655580	10,00000000	4,74655587
90	37,07659626	32.00000000	5,07659638
91	37,07659626	33,00000000	4,07659638
92	37,07659626	31,00000000	6,07659638
93	37,07659626	34.00000000	3,07659638
94	9,40701115	3.00000000	6,40701121
95	9,40701115	4.00000000	5,40701121
96	18,27739167	16,00000000	2,27739170
97	18,27739167	18,00000000	0,27739170
98	11,34936249	5.00000000	6.34936255
99	11,34936249	6,00000000	5,34936255
100	20,26671314	17,00000000	3,26671314
101	20,26671314	21,00000000	-0,73328684

Table 10

Normally Consolidated and Overconsolidated Reid Bedford Model Sand and Ottawa Sand Data

Test No.	N Predicted*	N Observed	Difference
5	10.9 (11)**	13	-2
11	7.9 (8)	8	0
13	12.8 (13)	11	+2
20	11.6 (12)	8	+4
21	8.8 (9)	11	-2
18	36.9 (37)	46	-9
7	15.9 (16)	16	0

* Equation 1 used to obtain predicted values.

** Rounded values used for difference calculations.

NOTE: Comparison of N-values predicted by Equation 1 with observed N-values which were excluded from the regression analysis.

Table 11

Comparison of Values Predicted by Equation 5

And the Observed Data

Set	D_R Predicted	D_R Observed	Difference
1	49,30177021	43,80000019	5,50177002
2	54,60941744	43,80000019	10,80941761
3	52,56331205	45,30000019	7,26331216
4	60,55993509	45,30000019	15,25993490
5	53,25576401	46,09999990	7,15576452
6	62,58716679	46,09999990	16,48716712
7	43,18914843	24,29999995	18,88914872
8	43,18914843	24,29999995	18,88914872
9	32,09719467	27,79999995	4,29719496
10	26,11293006	29,50000000	-3,38741976
11	40,41701317	27,79999995	12,61701333
12	33,36847162	29,50000000	3,86847198
13	57,83099747	59,00000000	-1,16900241
14	64,81456280	59,69999981	5,11456382
15	63,43304396	59,69999981	3,73304424
16	48,54083443	56,30000019	-7,75916552
17	48,54083443	56,30000019	-7,75916552
18	58,45033836	57,30000019	1,15033862
19	61,43827248	57,30000019	4,13827252
20	59,06207963	59,00000000	0,06207986
21	63,43304396	59,00000000	4,43304408
22	31,43503666	38,00000000	-6,56496322
23	27,78451848	38,00000000	-10,21548152
24	41,83199501	39,69999981	2,13199547
25	44,91989660	40,90000010	4,01989681
26	50,78248596	40,90000010	9,88248599
27	46,97372817	45,69999981	1,27372880
28	48,92309713	45,69999981	3,22309738
29	46,97372817	45,69999981	1,27372880
30	48,92309713	45,69999981	3,22309738
31	50,78248596	45,69999981	5,08248627
32	55,92437125	45,69999981	10,22437143
33	28,56807137	35,09999990	-6,53192854
34	35,16156673	35,09999990	0,06156685
35	35,16156673	35,09999990	0,06156685
36	40,41701317	35,09999990	5,31701338
37	37,90731048	35,09999990	2,80731103
38	79,31824303	71,50000000	7,81824386
39	75,98559952	71,50000000	4,48559976
40	70,03075600	71,50000000	-1,46924327
41	74,83746910	71,50000000	3,33746988
42	73,66908551	71,50000000	2,16908610
43	75,98559952	71,50000000	4,48559976
44	37,90731048	48,19999981	-10,29268896
45	37,90731048	48,19999981	-10,29268896
46	40,41701317	48,19999981	-7,78298652
47	40,41701317	48,19999981	-7,78298652
48	46,97372817	48,19999981	-1,22627120
49	38,42614746	27,09999990	11,32614779
50	38,42614746	27,09999990	11,32614779
51	38,42614746	27,09999990	11,32614779
52	38,42614746	27,09999990	11,32614779
53	66,42884064	73,19999981	-6,77115828
54	75,06868172	73,19999981	1,86868250
55	63,71211815	73,19999981	-9,48788154
56	69,02354908	73,19999981	-4,17644984
57	63,71211815	73,19999981	-9,48788154
58	69,02354908	73,19999981	-4,17644984
59	65,35775662	74,39999962	-9,04224217
60	76,43941116	74,39999962	2,03941193

(Continued)

Table 11 (Concluded)

Set	D_R Predicted	D_R Observed	Difference
61	72.95787525	74.39999962	-1.44212371
62	79.75080395	74.39999962	5.35080445
63	83.93994426	74.39999962	9.53994501
64	60.55993509	73.50000000	-12.94006490
65	64.81456280	73.50000000	-8.68543637
66	70.03075600	73.50000000	-3.46924329
67	66.16293812	73.50000000	-7.33706117
68	68.76911354	73.50000000	-4.73088586
69	68.76911354	73.50000000	-4.73088586
70	40.41701317	45.30000019	-4.88298690
71	48.92309713	45.30000019	3.62309700
72	42.74275780	45.30000019	-2.55724218
73	46.97372817	45.30000019	1.67372842
74	52.56331205	45.30000019	7.26331216
75	48.92309713	45.30000019	3.62309700
76	46.97372817	45.30000019	1.67372842
77	37.90731048	37.59999991	0.30731105
78	44.91989660	37.59999991	7.31989694
79	37.90731048	37.59999991	0.30731105
80	40.41701317	37.59999991	2.81701342
81	40.41701317	37.59999991	2.81701342
82	43.62985230	53.80000019	-10.17014778
83	47.76511907	53.80000019	-6.03488070
84	43.62985230	53.80000019	-10.17014778
85	43.62985230	53.80000019	-10.17014778
86	26.11258030	24.29999995	1.81258057
87	30.04949737	24.29999995	5.74949760
88	20.98189020	24.29999995	-3.31810963
89	26.11258030	24.29999995	1.81258057
90	63.98978615	74.30000019	-10.31021368
91	65.35775662	74.30000019	-8.94224275
92	62.58716679	74.30000019	-11.71283317
93	66.69352722	74.30000019	-7.60647291
94	43.18914843	56.09999990	-12.91085112
95	45.33984804	56.09999990	-10.76015162
96	54.27476502	59.19999981	-4.92523449
97	57.51838684	59.19999981	-1.68161294
98	47.37144280	59.80000019	-12.42855716
99	49.30177021	59.80000019	-10.49822998

Table 12

Normally Consolidated and Overconsolidated Reid

Bedford Model Sand and Ottawa Sand Data

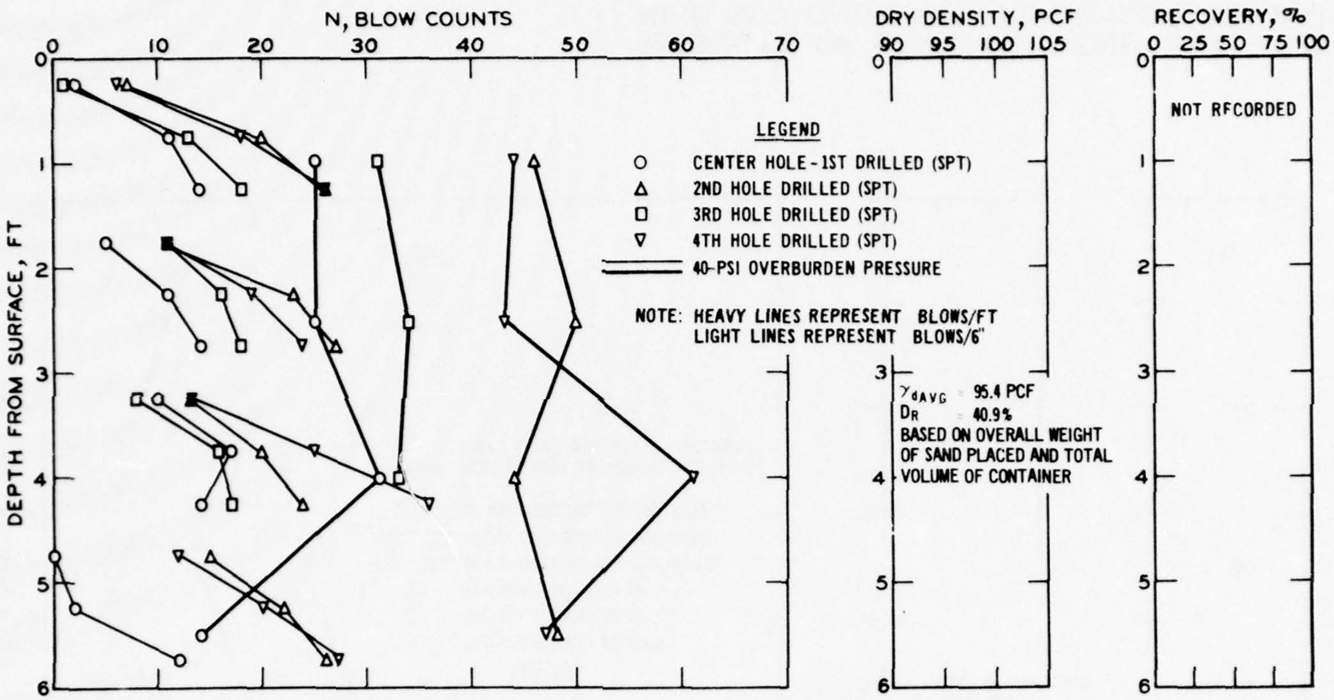
Test No.	D_R Predicted* percent	D_R Measured* percent	Difference percent
5	60.8	59.0	+1.8
11	37.9	35.1	+2.8
13	44.9	48.2	-3.3
20	37.9	45.3	-7.4
21	44.9	37.6	+7.3
18	80.7	74.4	+6.3
7	41.8	39.7	+2.1

* Equation 5 used to predict values for comparison of relative densities predicted by Equation 5 with observed relative densities which were excluded from the regression analysis.

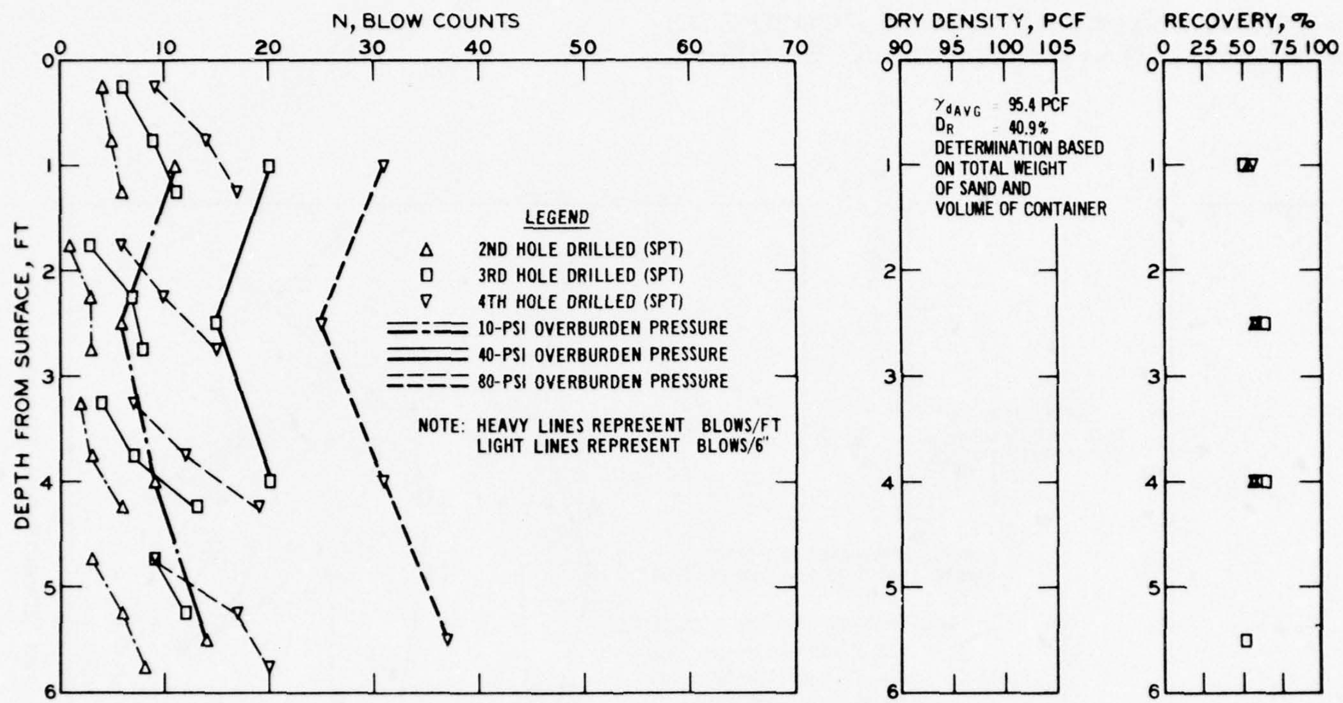
Table 13

Variations in Technique and Equipment Between the Bureau of Reclamation and WES SPT Studies

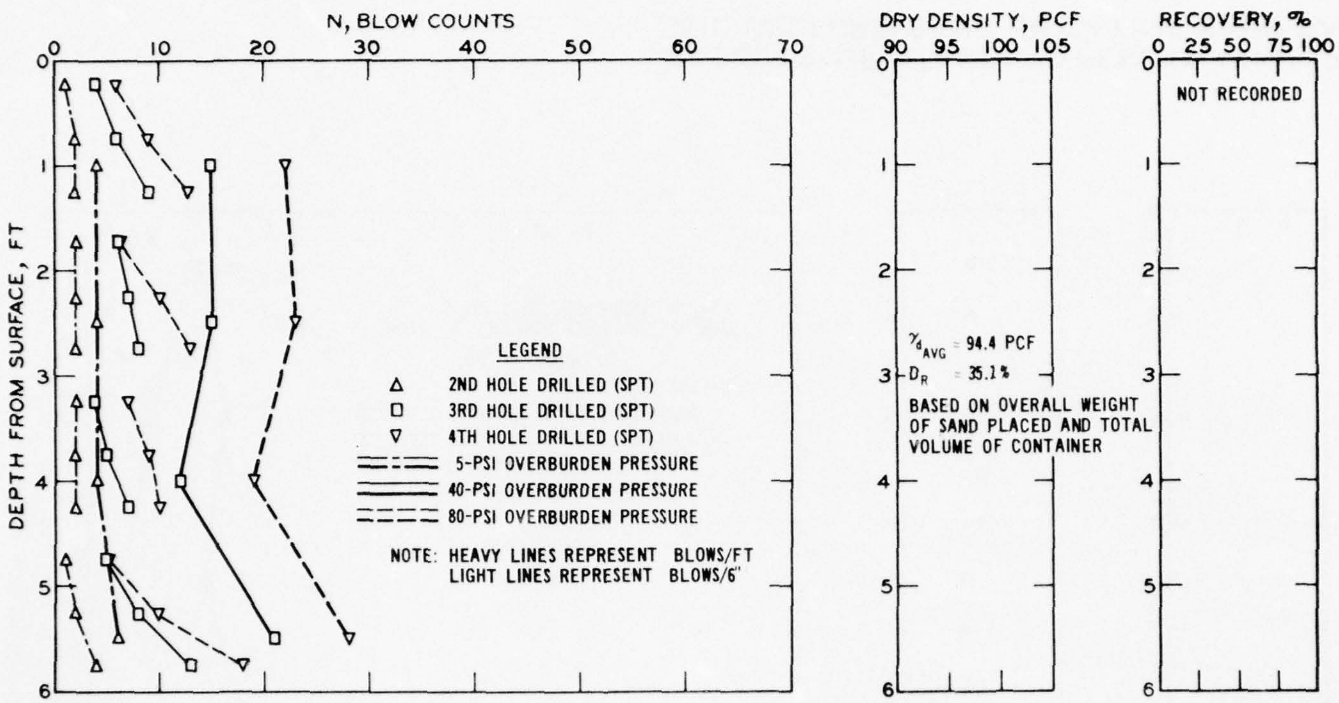
	Bureau of Reclamation Tests	Waterways Experiment Station Tests
1.	Applied overburden pressure by means of rigid plates and springs	Applied overburden pressure with flexible, reinforced rubber water bag
2.	Soil container was a solid wall tank 3 ft 1-1/2 in. in diameter	Soil container was a layer system of alternating steel and rubber rings, to provide flexibility in the vertical direction
3.	Cathead with an unstated number of wraps was used	Trip hammer
4.	Penetration tests were made through 6 holes in the loading plate	Penetration tests were made through a maximum of 4 holes
5.	Sand placement was by lift; compaction was by a vibrator	Various sand placement techniques
6.	Testing performed on submerged and dry specimens; recommendations were developed from the dry sand results	Testing performed on submerged specimens



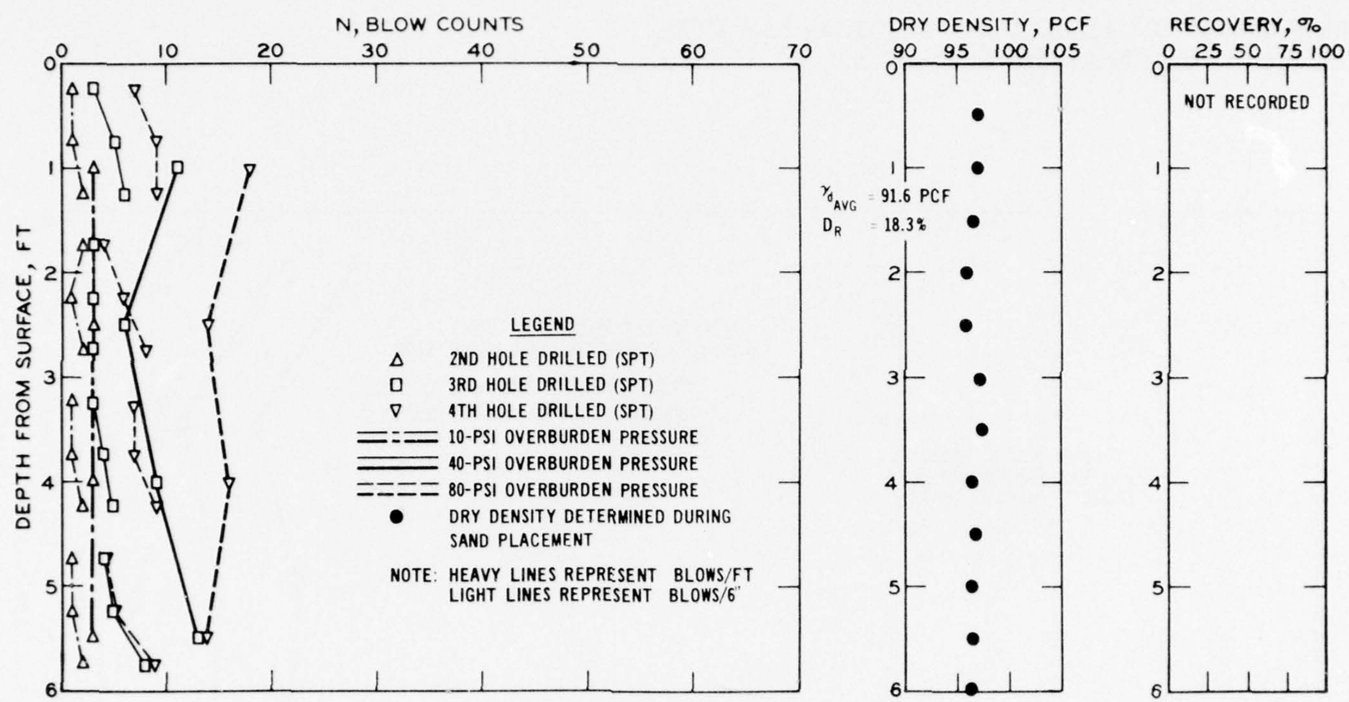
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 1, MAR 1973



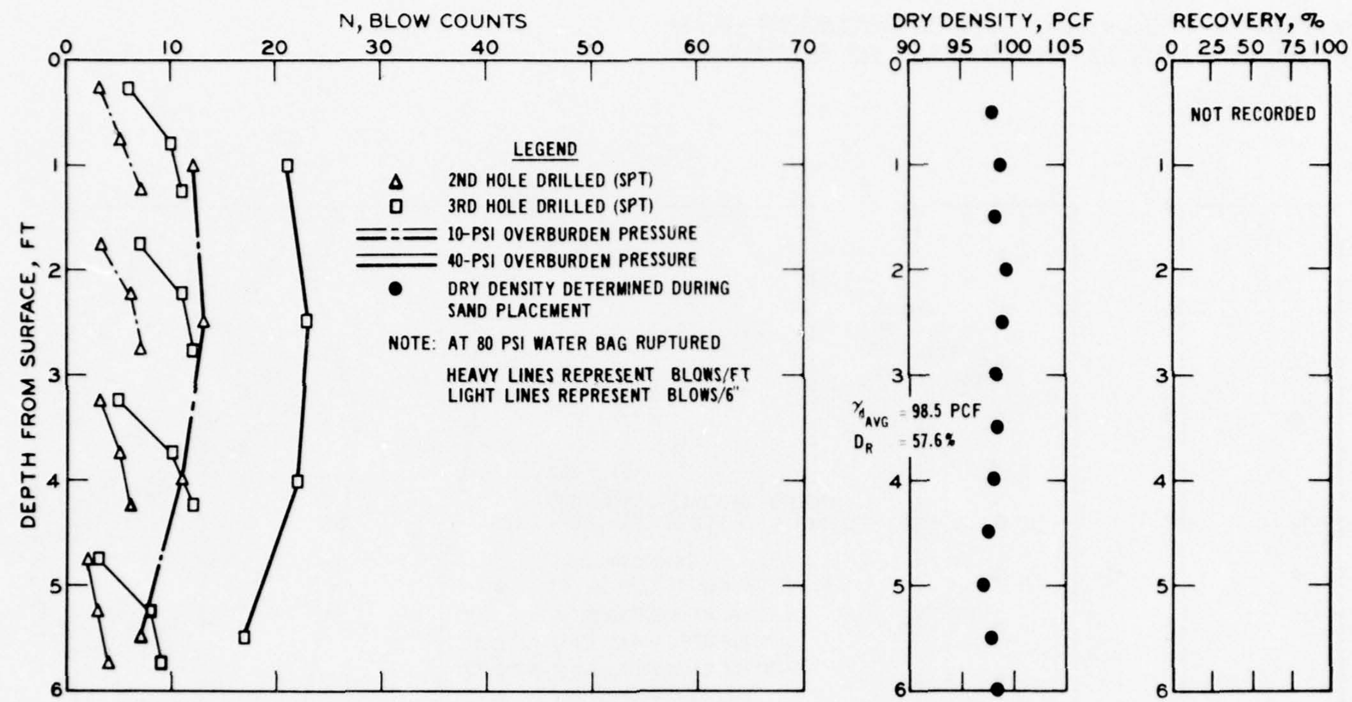
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 2, MAR 1973



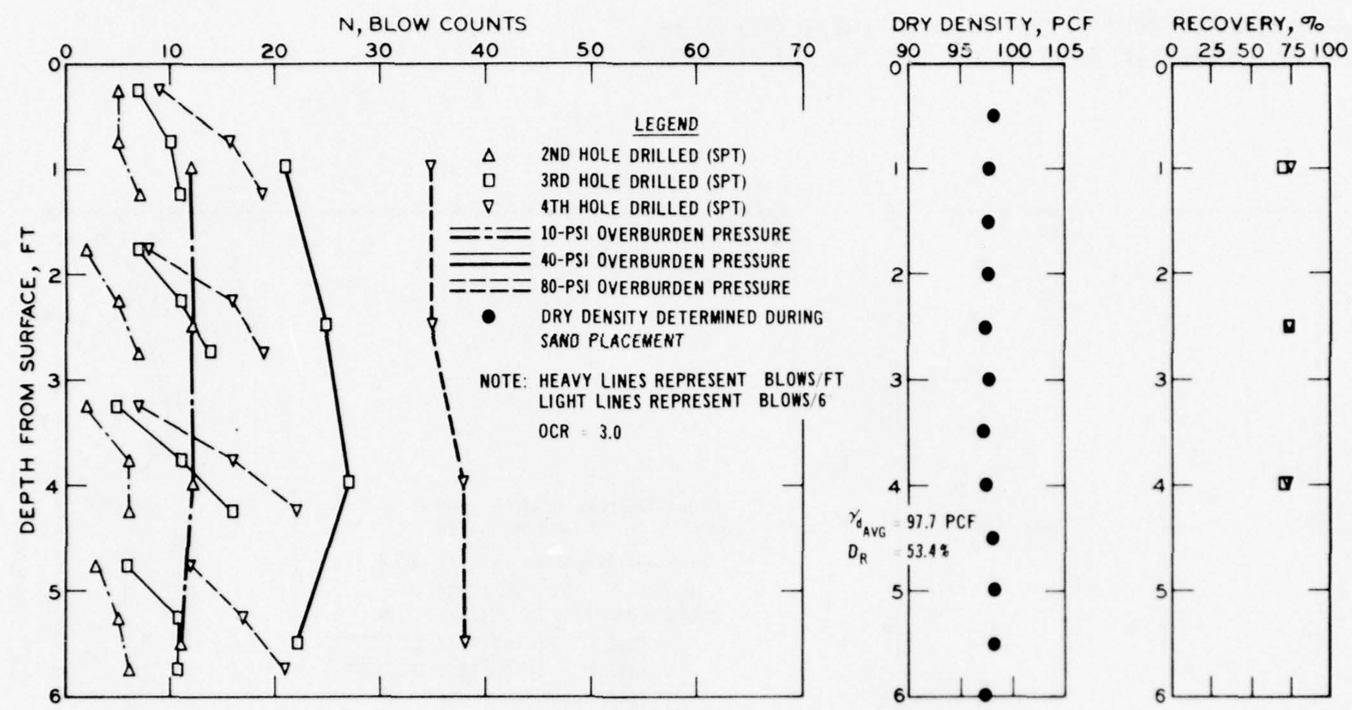
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 3, MAR 1973



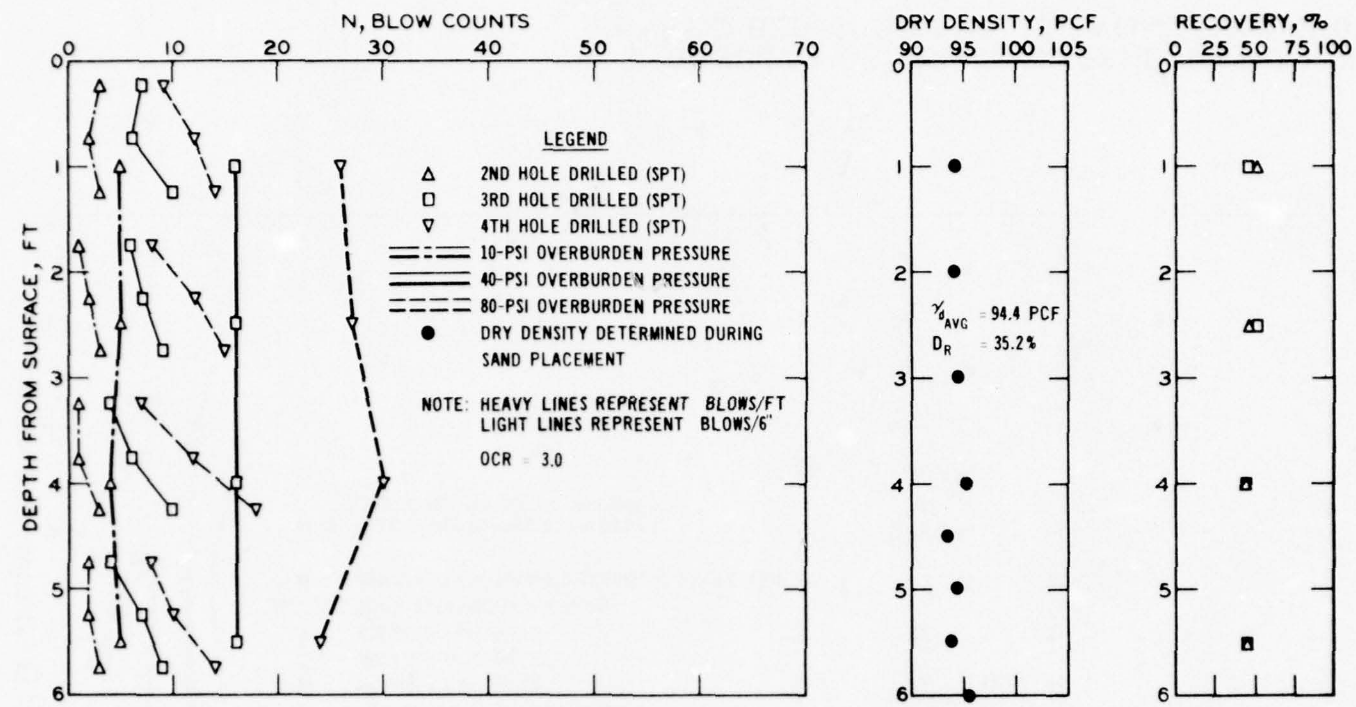
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 4, APR 1973



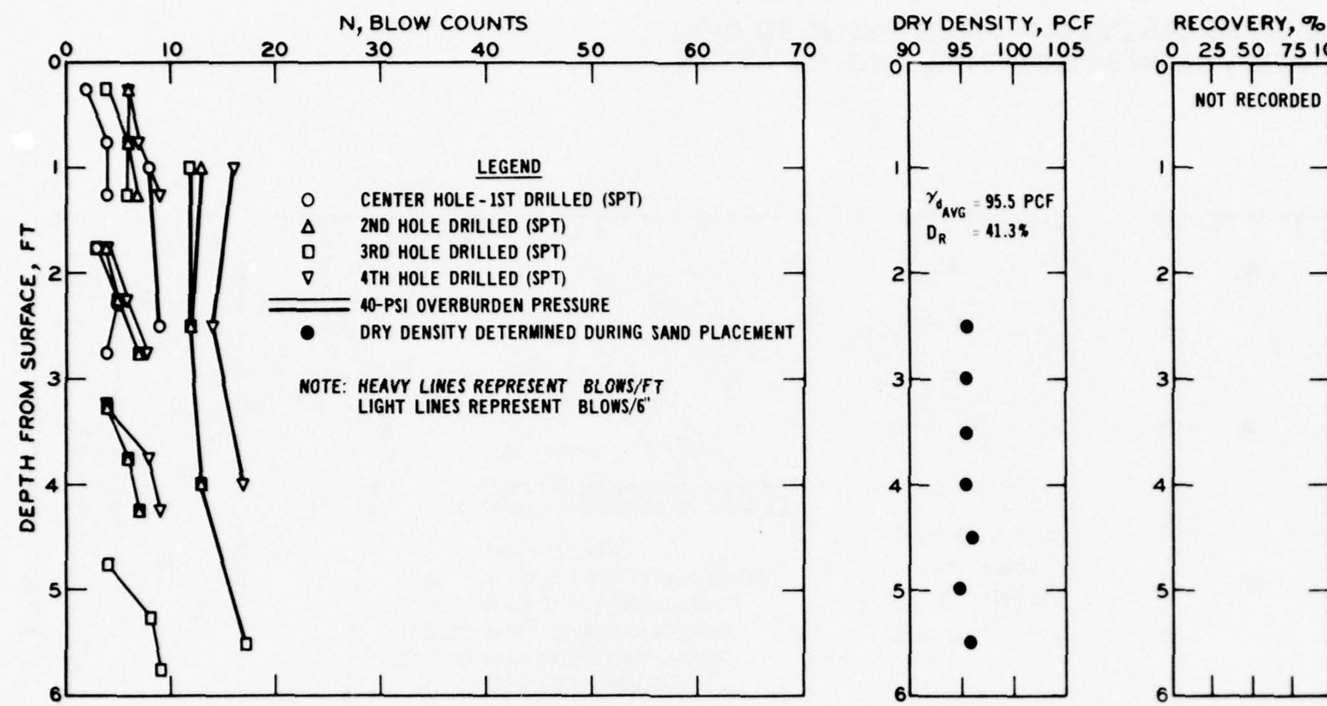
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 5, APR 1973



RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 6, APR 1973

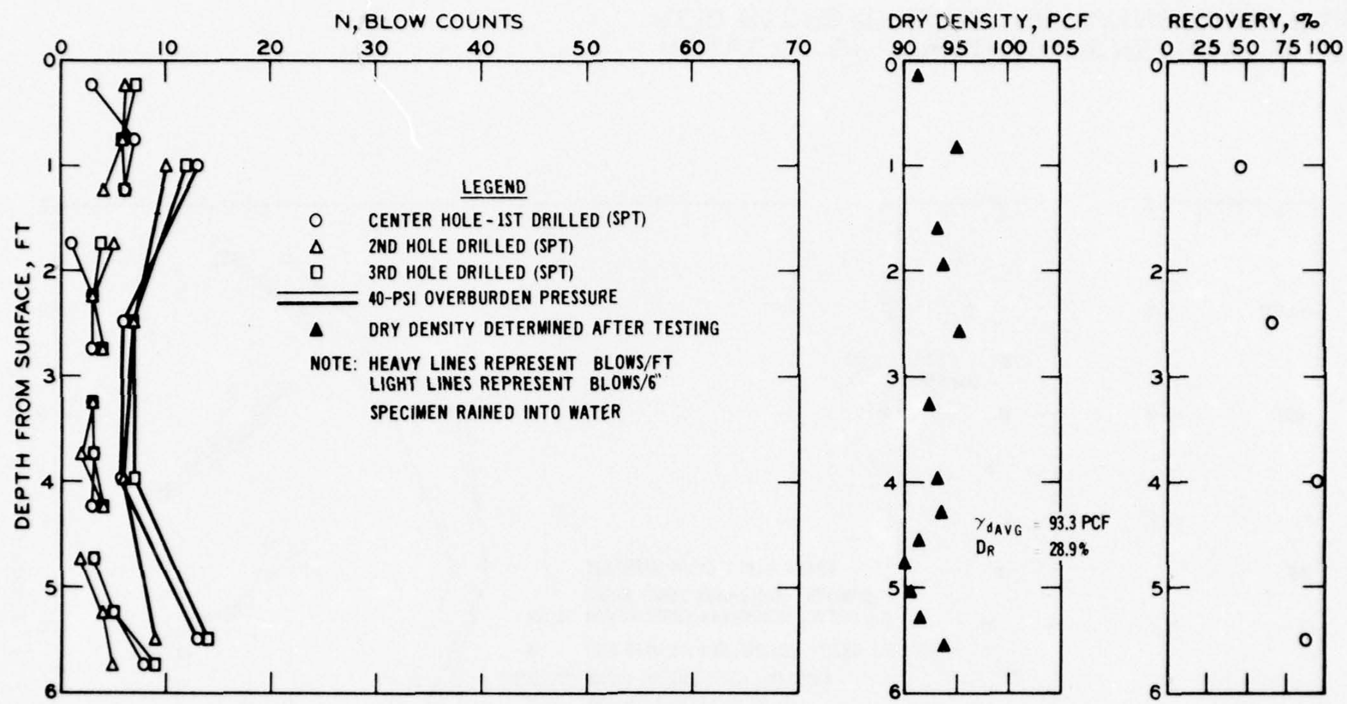


RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 7, APR 1973

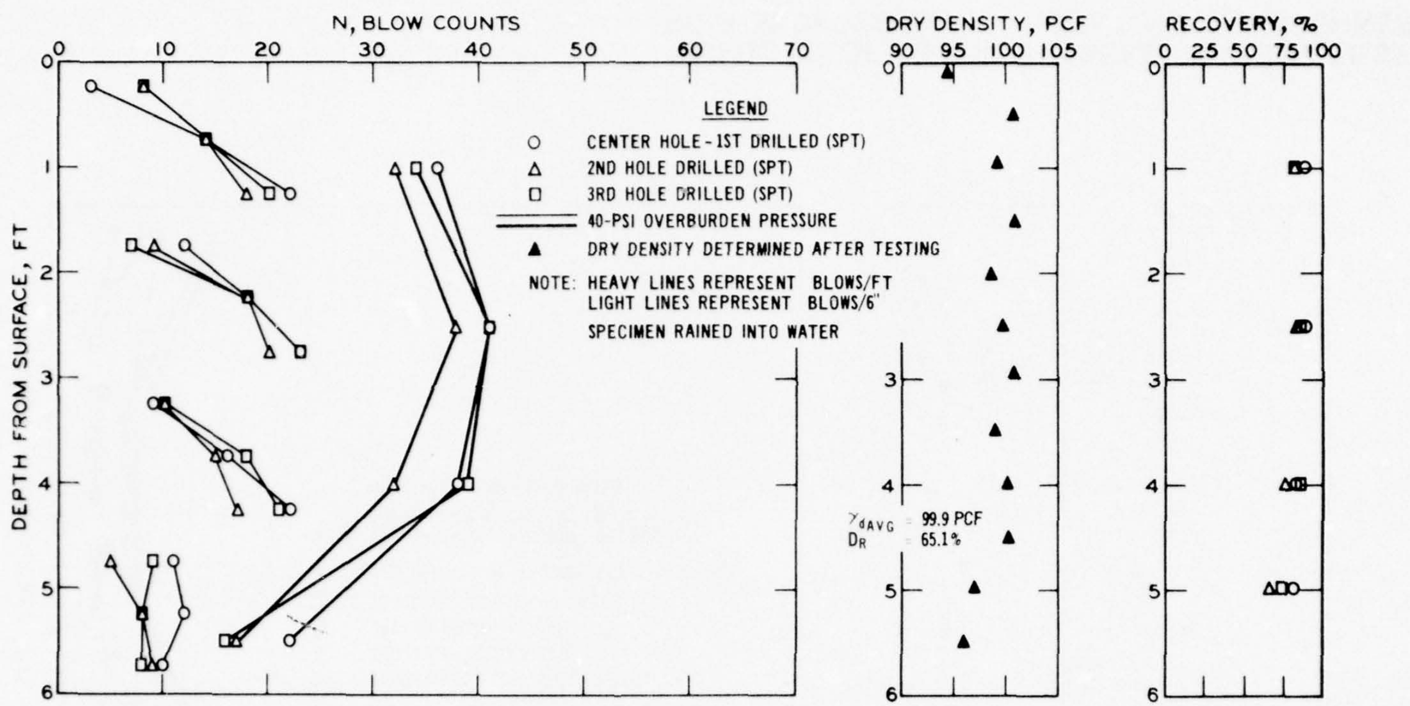


RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 8, DEC 1973

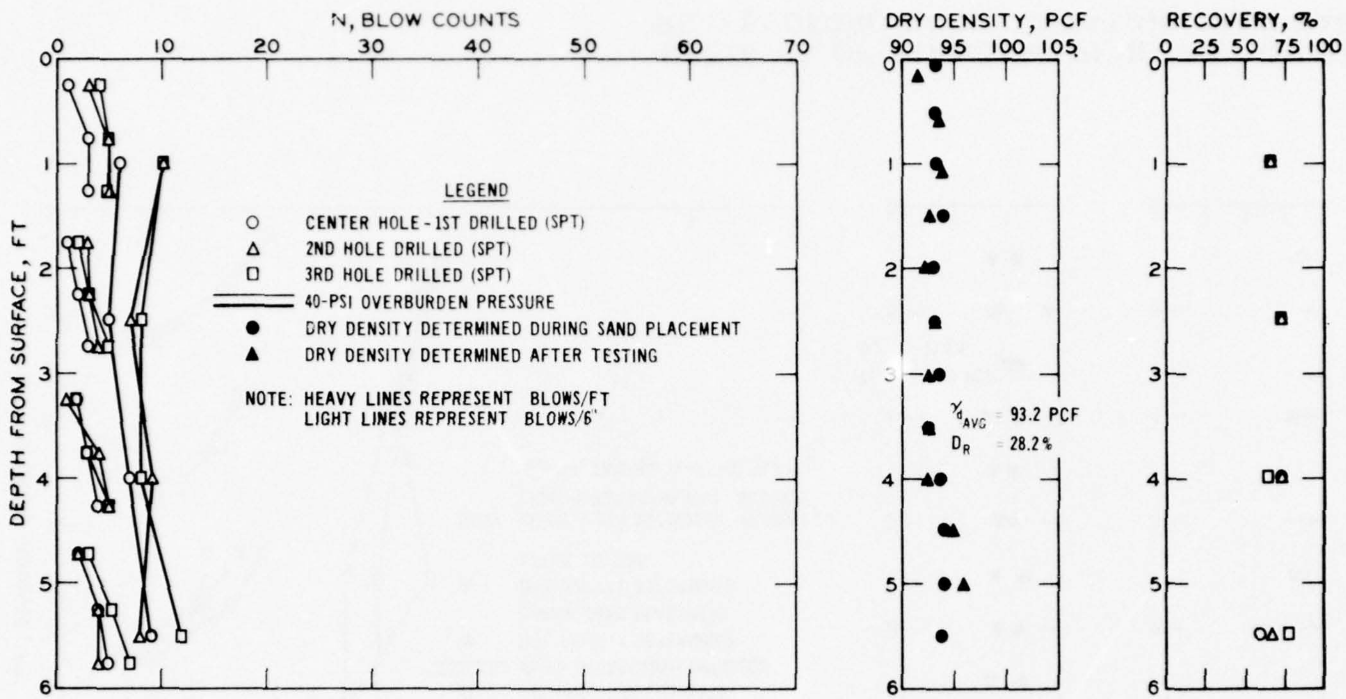
PLATE 8



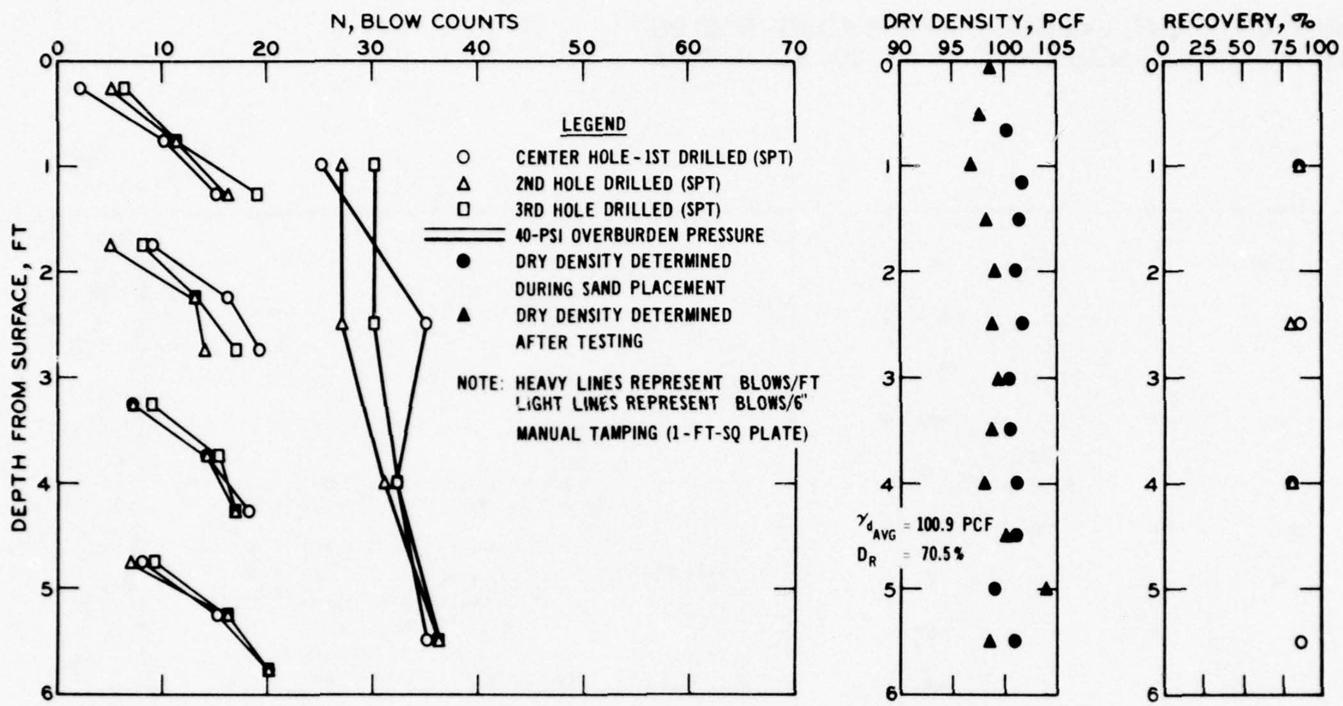
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 9, MAY 1974



RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 10, JUN 1974

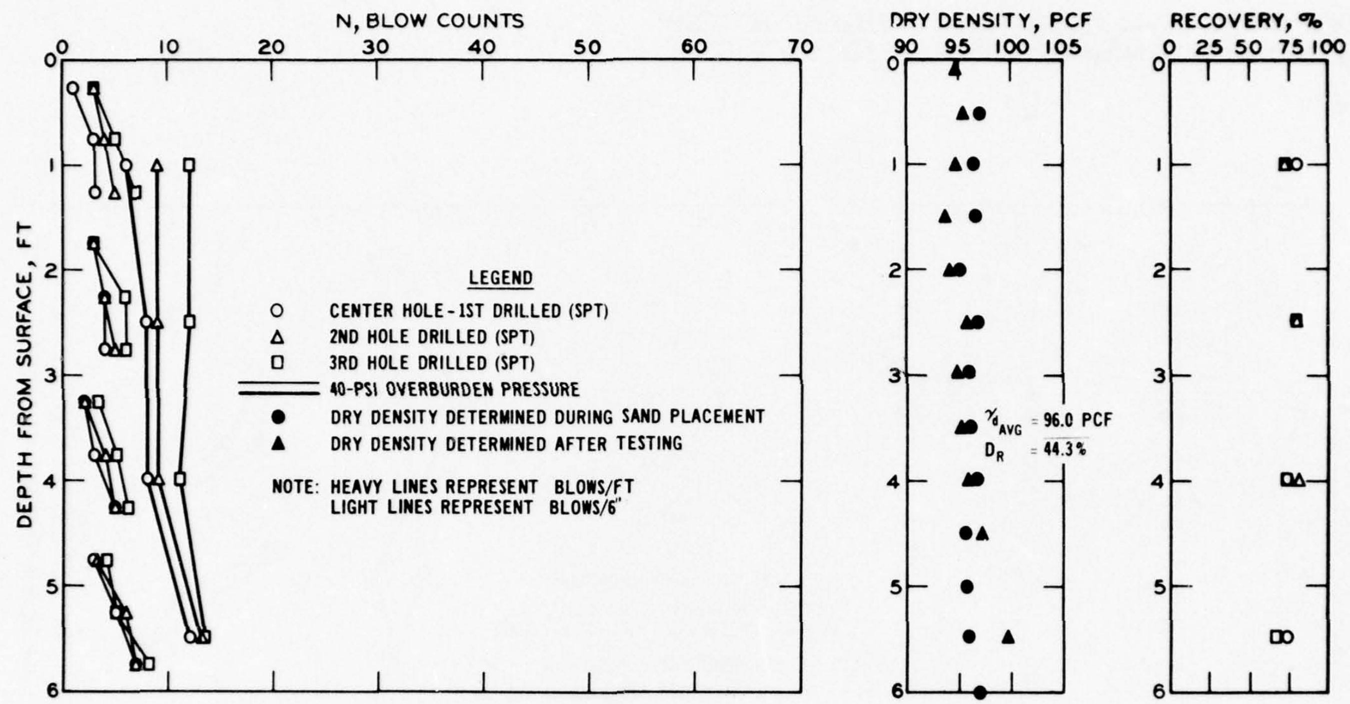


RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 11, JUL 1974

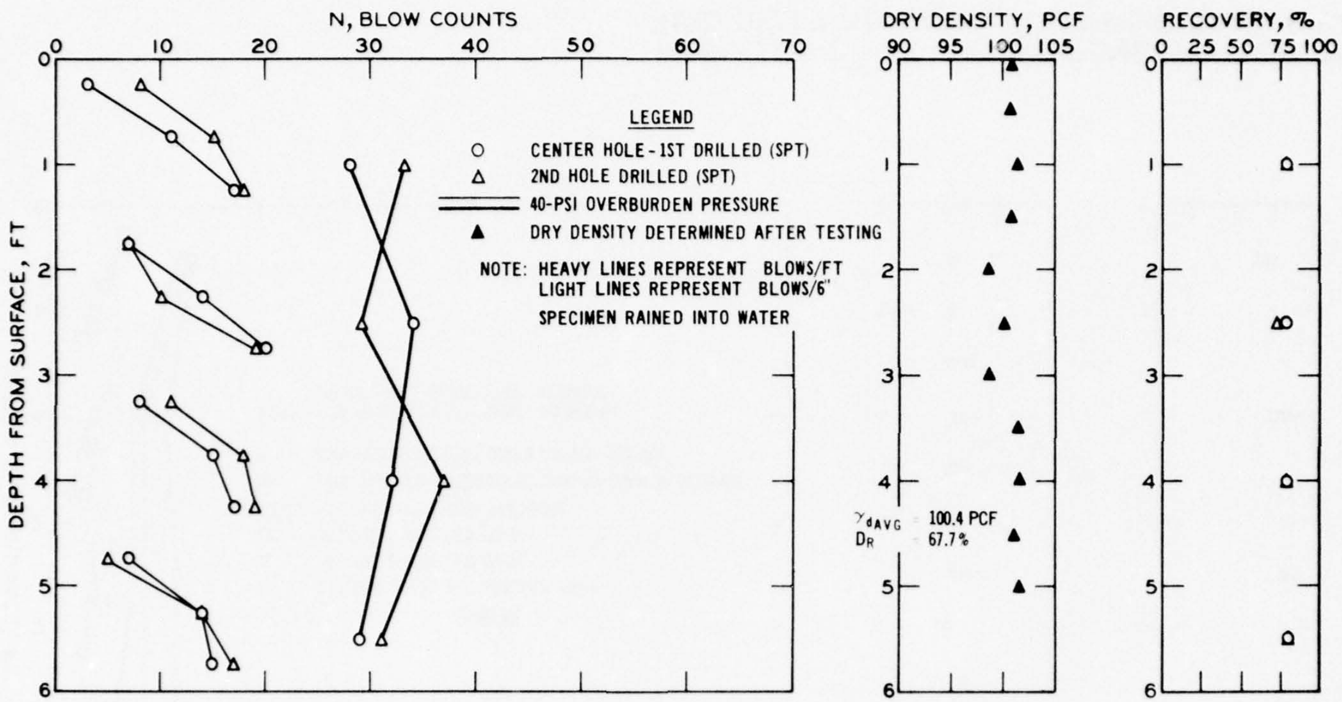


RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 12 JUL 1974

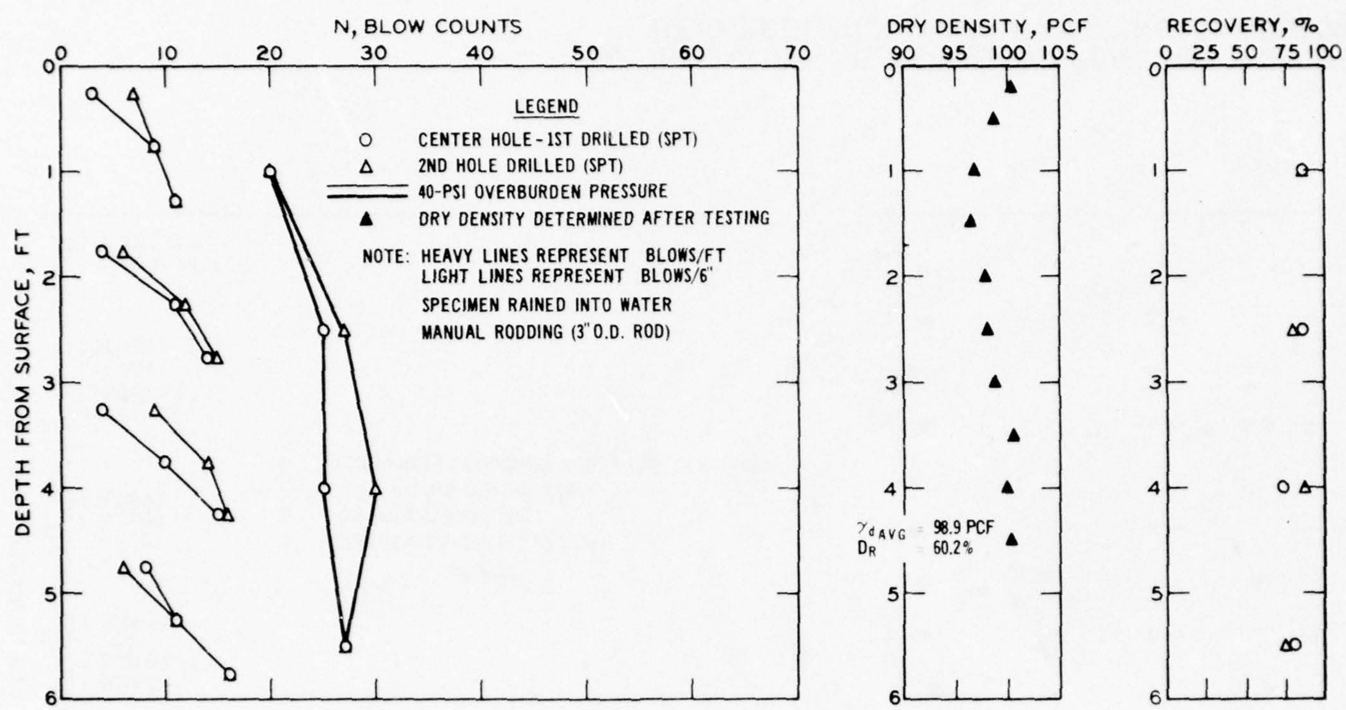
PLATE 12



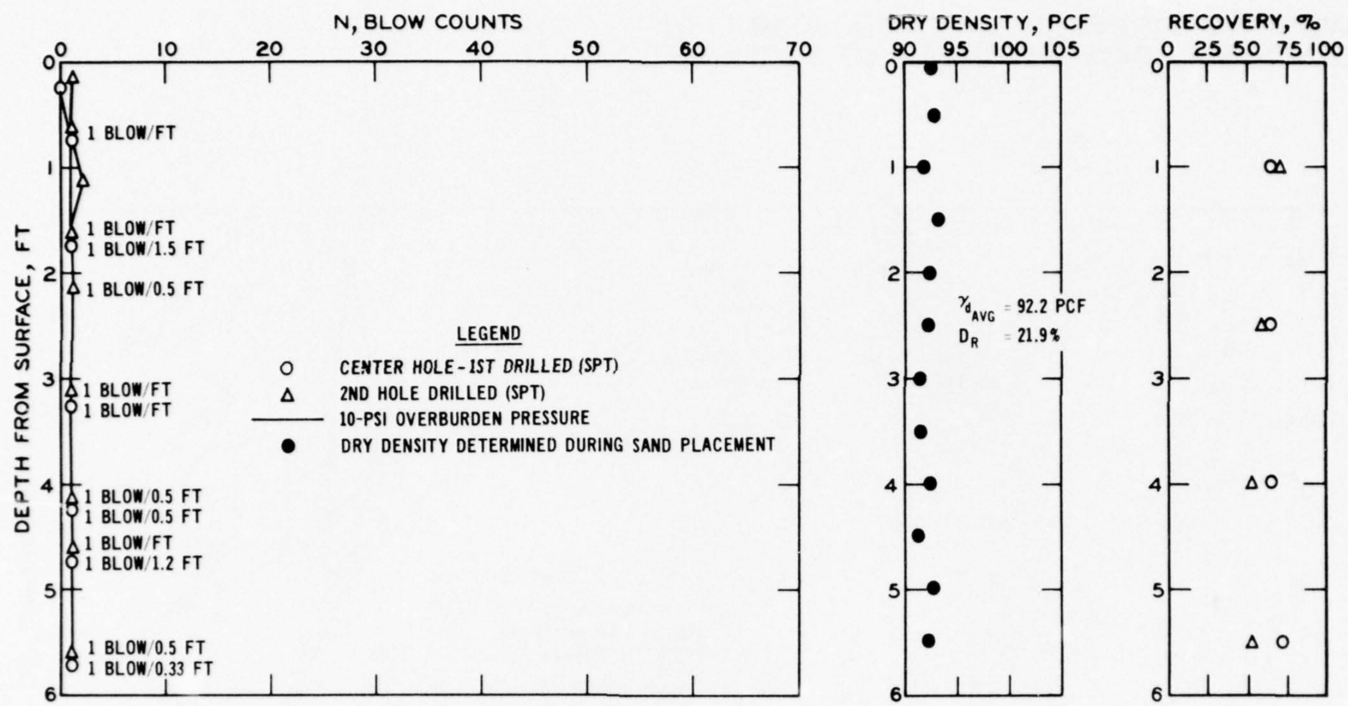
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 13, JUL 1974



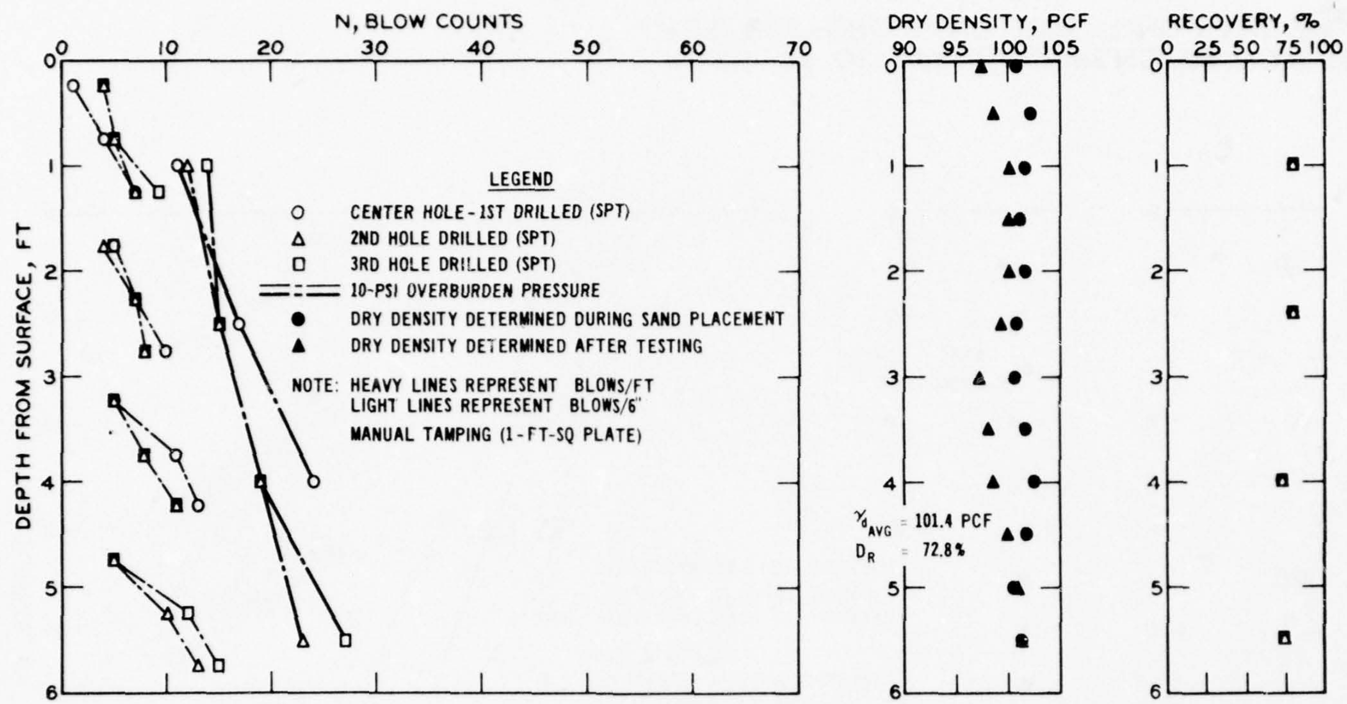
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 14, JUL 1974



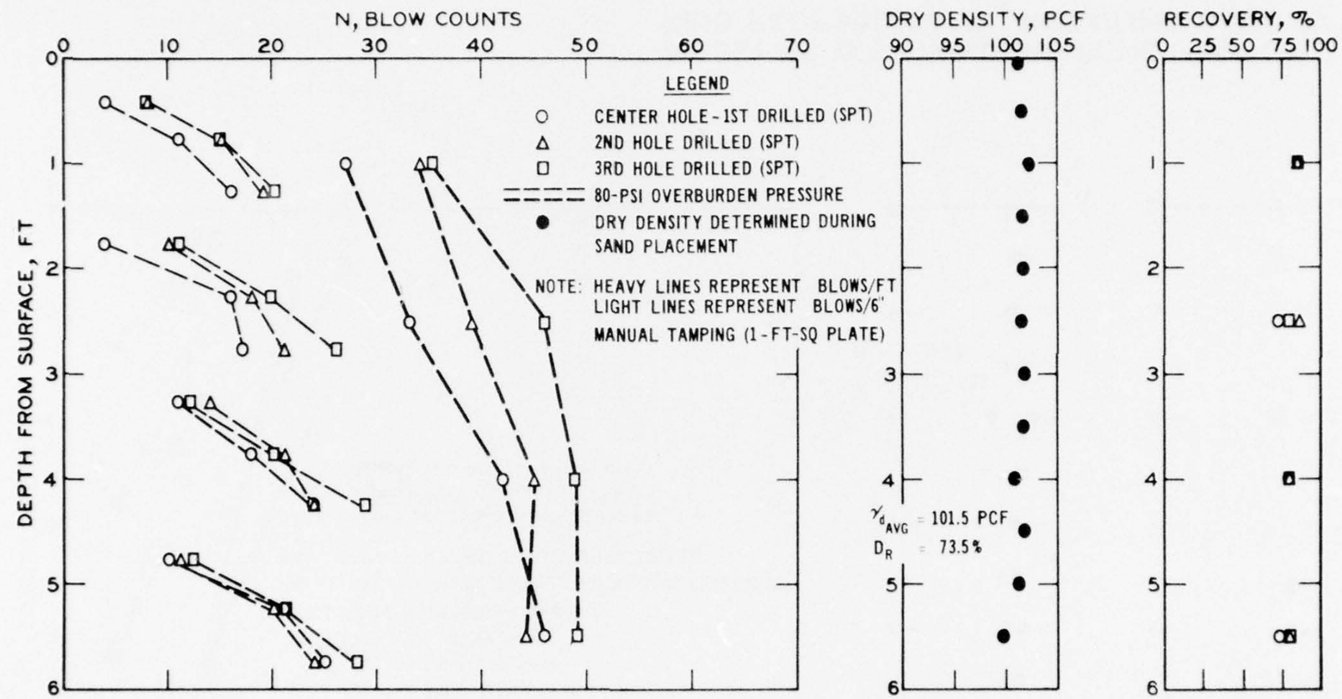
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 15, AUG 1974



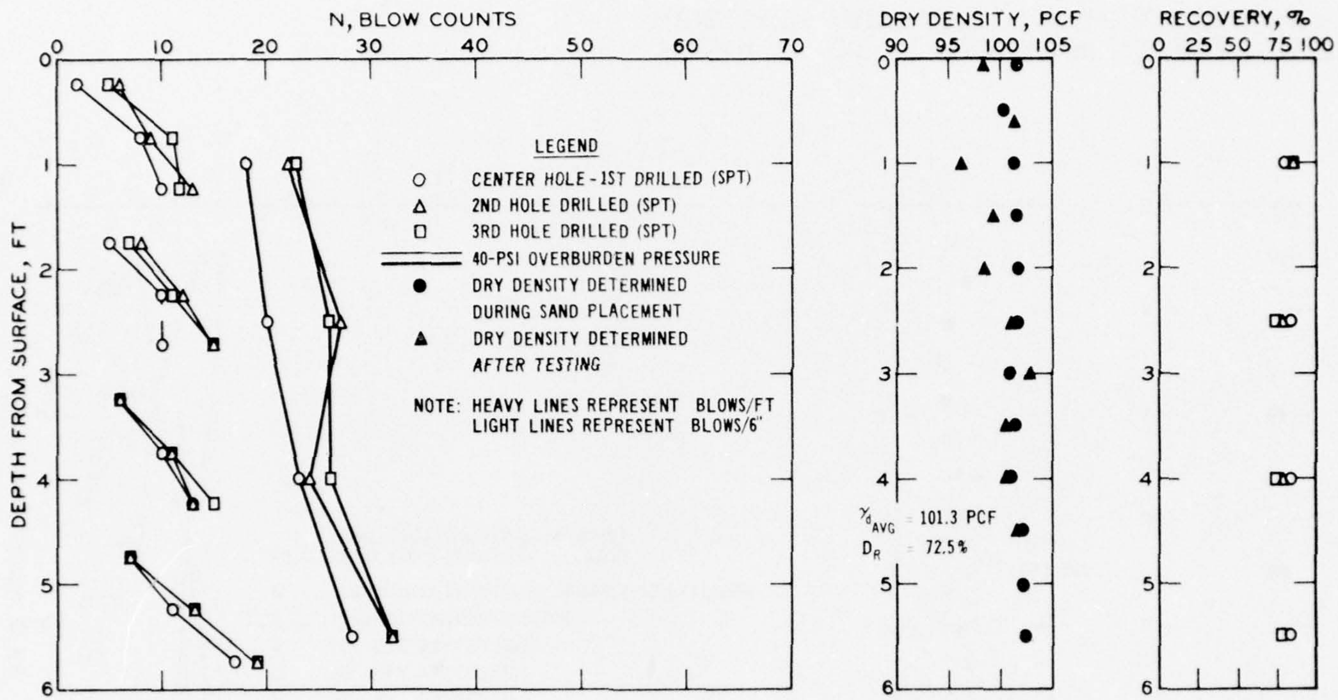
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 16, AUG 1974



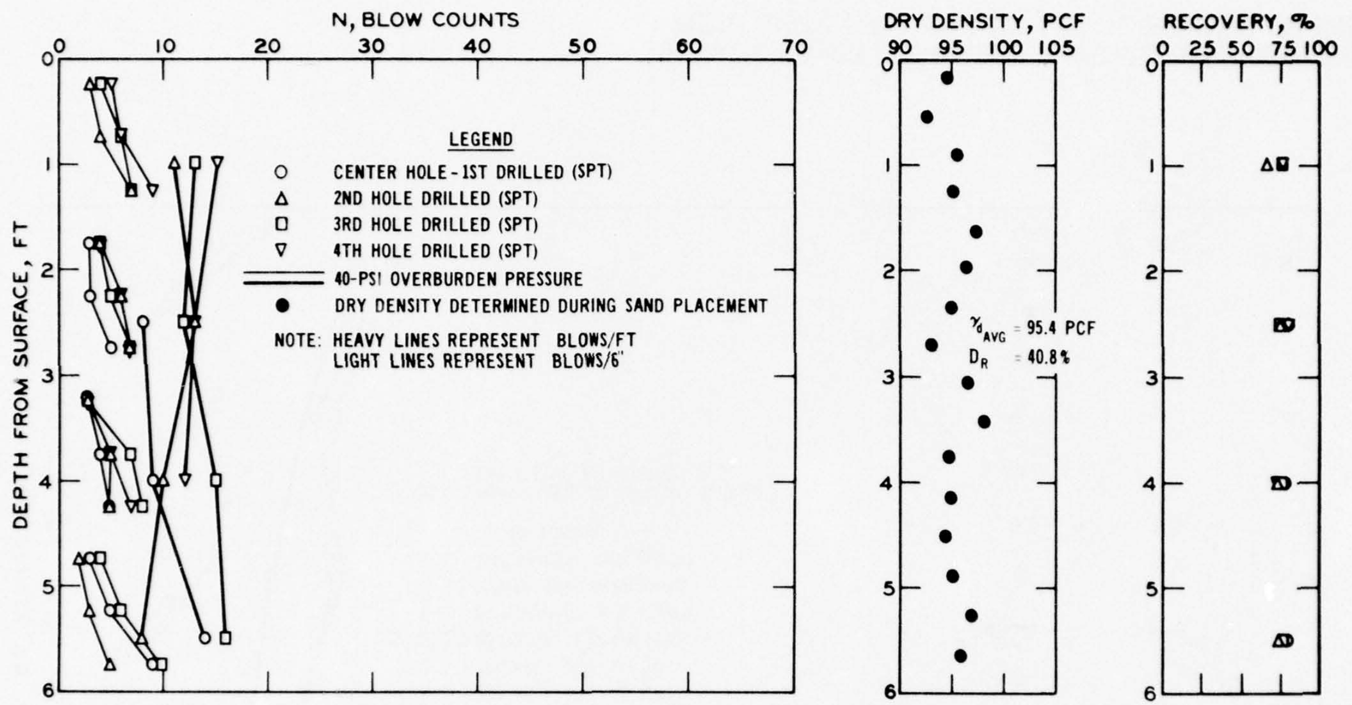
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 17, AUG 1974



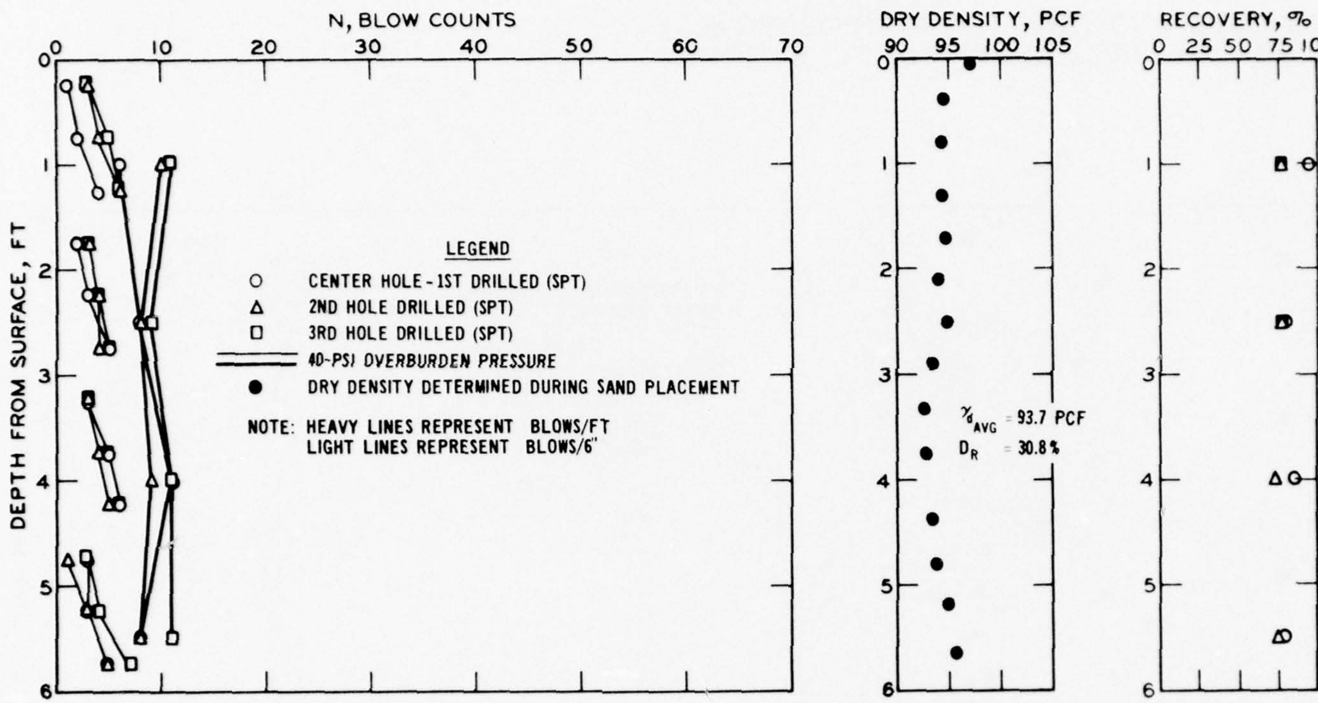
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, ROTATING SAND RAINER
TEST 18, SEP 1974



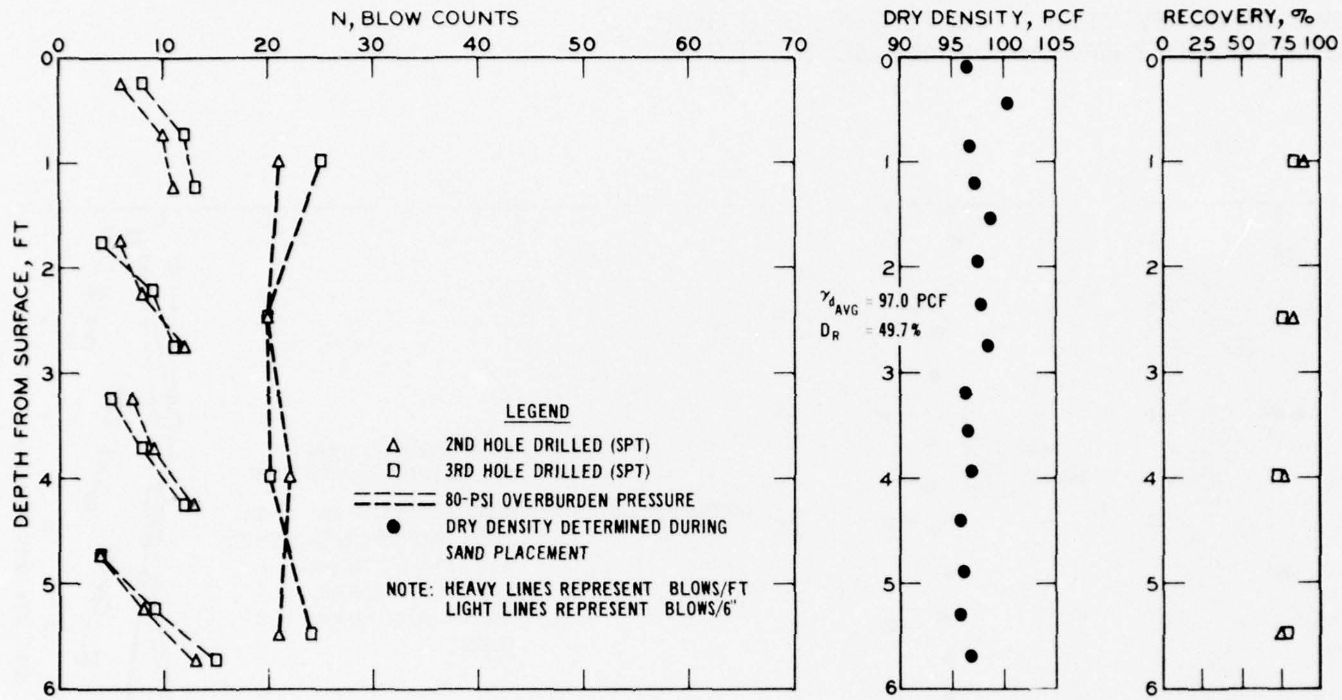
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, SINGLE-HOSE RAINER
TEST 19, SEP 1974



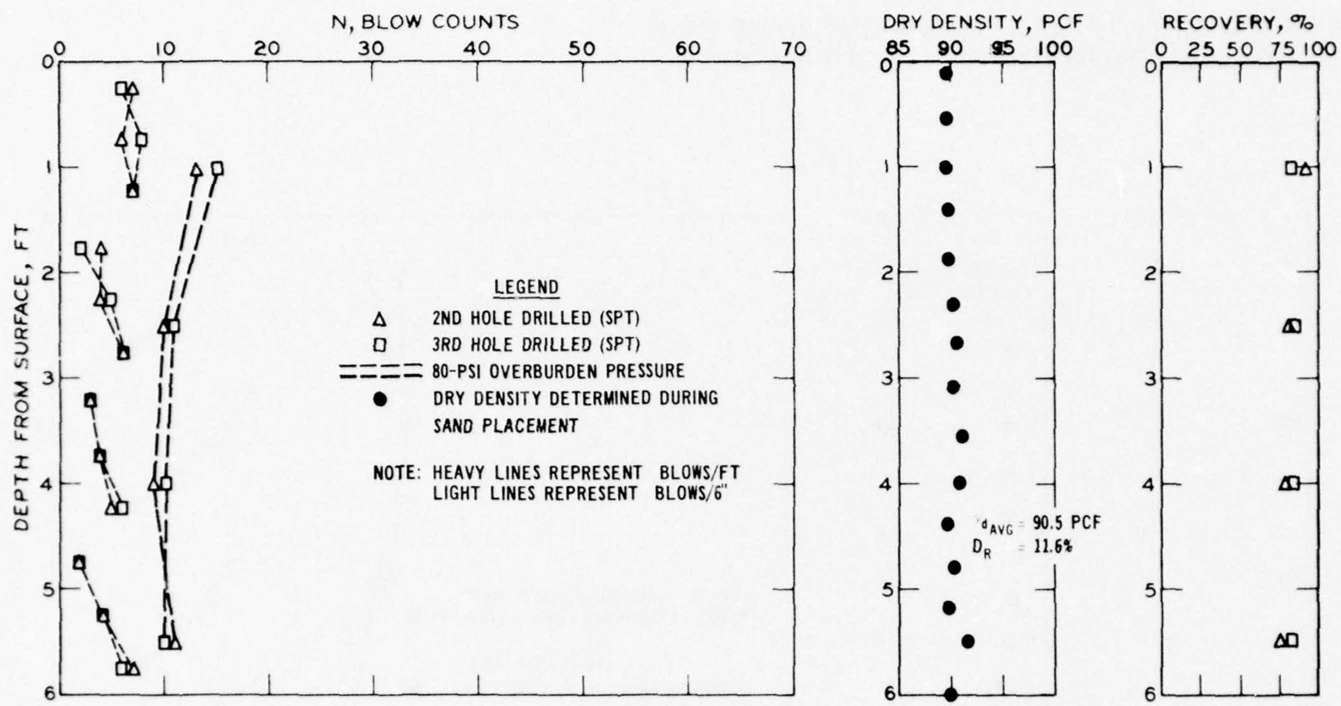
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, CIRCULAR SAND RAINER
TEST 20, NOV 1974



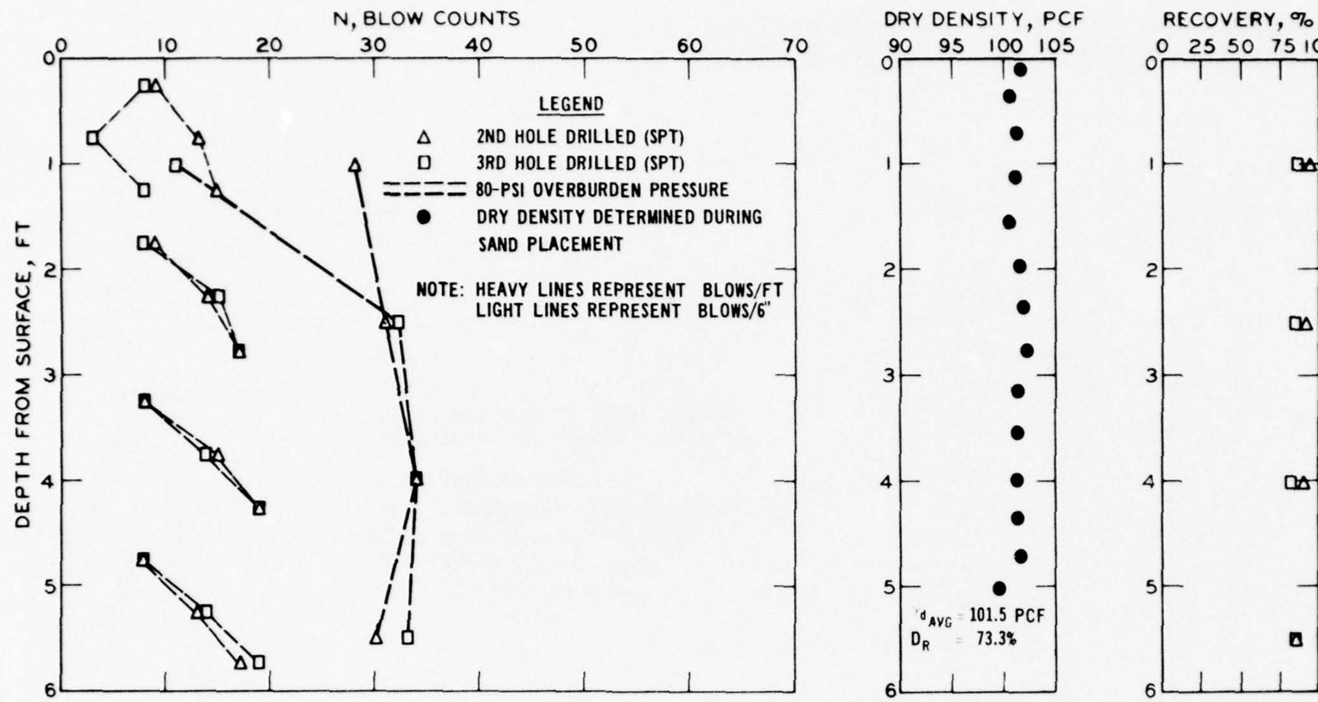
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, CIRCULAR SAND RAINER
TEST 21, DEC 1974



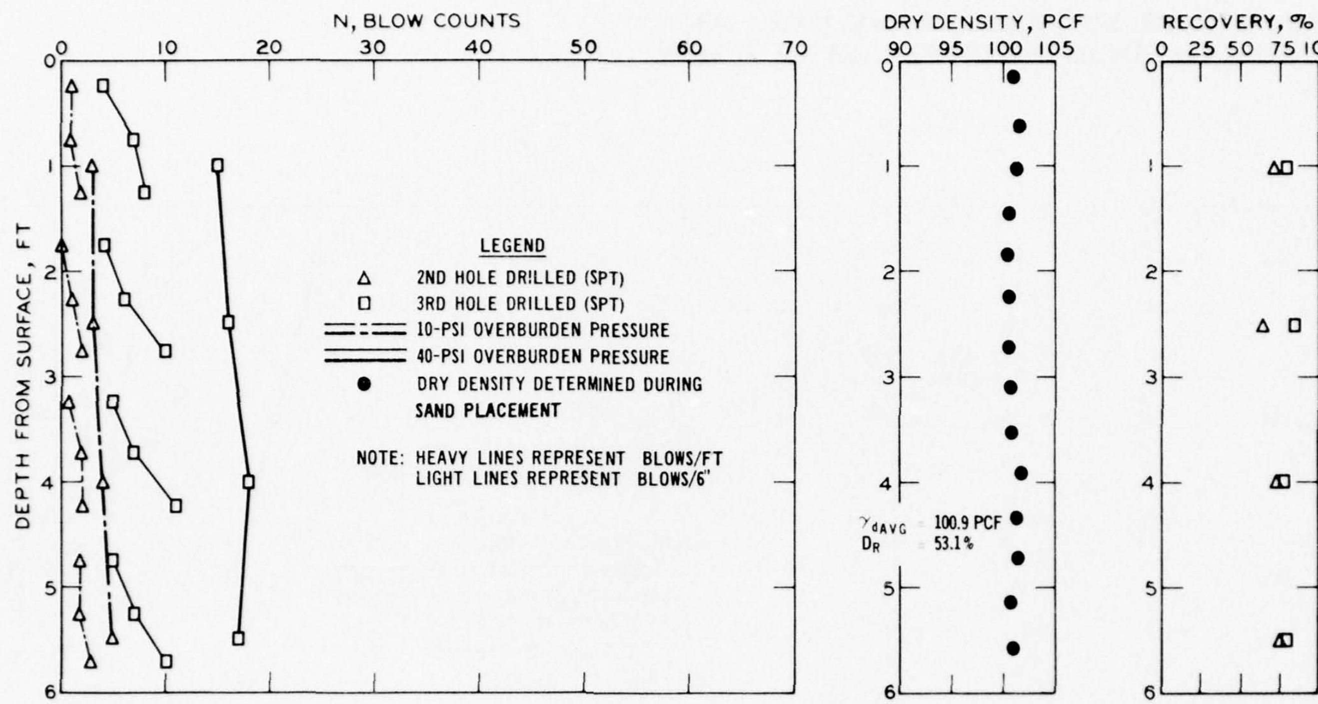
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, CIRCULAR SAND RAINER
TEST 22, JAN 1975



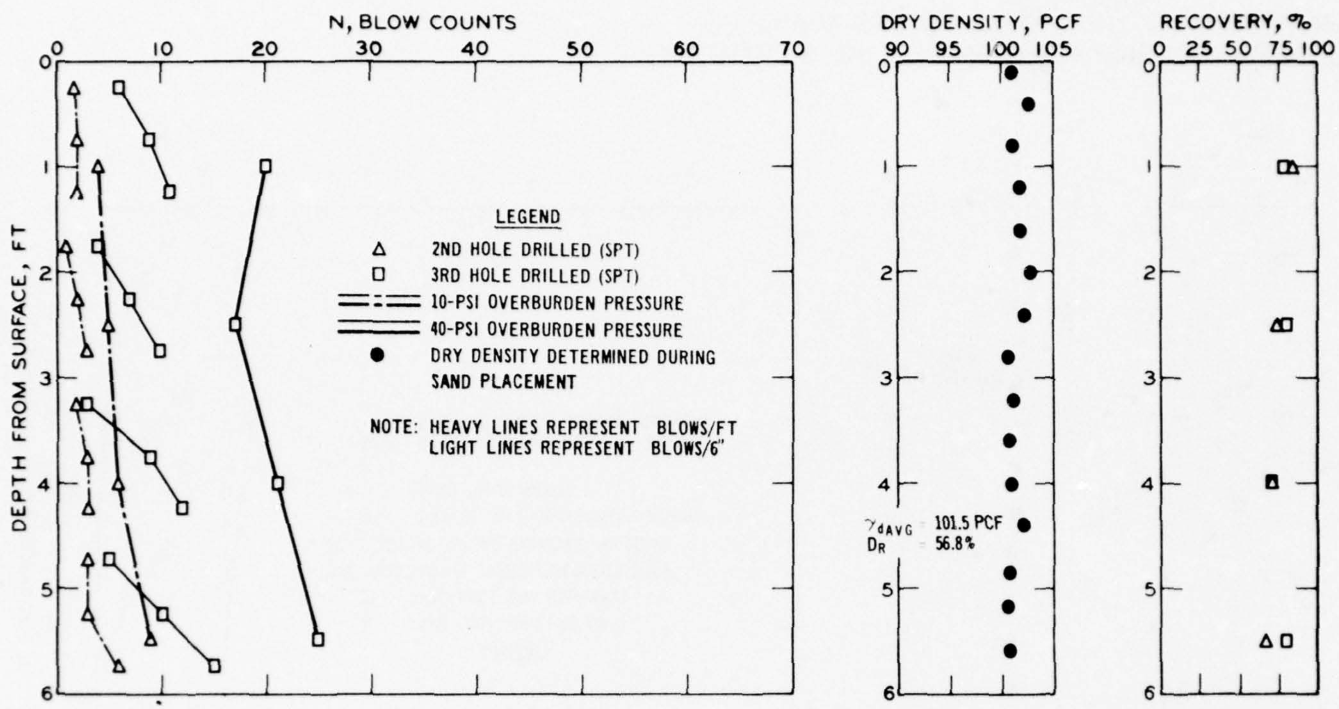
RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, CIRCULAR SAND RAINER
TEST 23, JAN 1975



RESULTS OF STANDARD PENETRATION TEST
REID BEDFORD SAND, CIRCULAR SAND RAINER
TEST 24, FEB 1975



RESULTS OF STANDARD PENETRATION TEST
OTTAWA SAND, CIRCULAR SAND RAINER
TEST 25, APR 1975



RESULTS OF STANDARD PENETRATION TEST
OTTAWA SAND, CIRCULAR SAND RAINER
TEST 26, APR 1975

APPENDIX A: PETROGRAPHIC EXAMINATION OF THE REID BEDFORD MODEL SAND

DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
P. O. BOX 631
VICKSBURG, MISSISSIPPI 39180

IN REPLY REFER TO: WESSG

23 April 1974

MEMORANDUM FOR: Dr. W. F. Marcuson

SUBJECT: Petrographic Examination of the Reid-Bedford Model Sand

General

1. A sample of the Reid-Bedford model sand was analyzed by petrographic and statistical techniques for the purpose of determining gross mineralogy, degree of grain roundness, and the basic statistical parameters exhibited by this sediment.

Size-distribution statistics

2. Grain-size data obtained from the gradation curve were recalculated in phi (Ø)* units and plotted on probability paper. The resulting curve permitted the mean and median grain size, standard deviation, skewness, and the kurtosis to be calculated. These parameters are summarized below.

a. Mean grain size: $2.00\ \text{Ø} \approx 0.25$ mm. This corresponds to the division between medium and fine sand.**

b. Median grain size: $2.00\ \text{Ø} \approx 0.25$ mm.

c. Standard deviation: $0.50\ \text{Ø} = 0.71$ mm. The following classification is used here:

Very well sorted: < 0.35 Ø.
Well sorted: 0.35-0.50 Ø.
Moderately well sorted: 0.50-0.71 Ø.
Moderately sorted: 0.71-1.00 Ø.
Poorly sorted: 1.00-2.00 Ø.

Thus the Reid-Bedford sand is well to moderately well sorted.

* mm = $2^{-\text{Ø}}$

d. Skewness: -0.03 where

+0.3 to +1.00: strongly fine skewed
+0.1 to +0.3: fine skewed
-0.1 to +0.1: near symmetrical
-0.3 to -0.1: coarse skewed, etc.

The Reid-Bedford is, therefore, nearly symmetrical in distribution.

e. Kurtosis: 1.54. This value indicates a very leptokurtic curve where

$< 0.67 \longrightarrow$ very platykurtic
0.67 to $0.90 \rightarrow$ platykurtic
0.90 to $1.11 \rightarrow$ mesokurtic
1.11 to $1.50 \rightarrow$ leptokurtic
1.50 to $3.00 \rightarrow$ very leptokurtic

Petrography

3. General. The sand was examined by both nonpolarizing binocular and polarizing microscopes. The nonpolarizing type facilitates the examination of the coarser particles, whereas the finer fractions require polarized light. In order to determine any variation in rounding and mineralogy with respect to grain size, the sample was sieved through the No. 35, 60, 120, 200, and 300 mesh sieves. Grain mounts using Lakeside 70 were prepared for the No. 120, 200, and 300 mesh splits and for the pan fraction.

4. Particle morphology (general). Two important elements of particle morphology are sphericity and roundness. Sphericity relates to a particle's equidimensionality, whereas roundness is a parameter that describes the extent of "rough edges" on the particle surface. These parameters are not necessarily related; a prismatic grain, for example, could have a highly rounded surface. Quantitative values may be determined for both sphericity and roundness, but this is a time-consuming task (especially for sphericity) and was not done here. Instead, roundness was estimated from the index forms shown below.

A B C D E

Roundness classes. A: Angular. B: Subangular. C: Subrounded. D: Rounded. E: Well Rounded.

5. Preliminary examination of gross sample with nonpolarizing, binocular microscope. The sand consists predominantly of tan to light brown quartz sand. Two types may be distinguished as (a) a clear, unweathered, subangular type, and (b) a cloudy, less angular variety. These two types comprise roughly subequal proportions of the sample. Possibly some of the cloudy grains are feldspar. Moscovite mica is present and comprises less than 5 percent of the sample; the mica is considerably coarser ($\sim$1.00 mm) than the accompanying quartz. Identifiable "heavy" minerals include tourmaline, garnet, and presumed amphibole-pyroxene minerals; no magnetic minerals were detected. The heavies are estimated to comprise no more than 1-2 percent of the total sample. The sample appears free of visible organic matter.

6. Examination of sieve splits. Examination of sieve splits consisted of the following sieves:

a. Sieve No. 35 (nonpolarizing). Predominantly subrounded to subangular grains of quartz; varieties include both clear and cloudy. The cloudy grains appear to have polished surfaces. Chert, ferromags, a siltstone rock fragment, and calcite concretions comprise approximately 1 or 2 percent of the split.

b. Sieve No. 60 (nonpolarizing). Very similar to sieve No. 35 except that there is an apparent slight increase in heavy mineral concentration (ferromags, garnet, etc.)

c. Sieve No. 120 (polarizing). Rounding; subangular; grain count revealed approximately 88.5 percent quartz and 11.5 percent feldspar. Although no other minerals were encountered in the count traverses, the nonquartz or feldspar content is probably around 1 percent or less.

d. Sieve No. 200 (polarizing microscope). Rounding; subangular; mineralogy is 92.3 percent quartz, 5.6 percent feldspar, and 2.1 percent opaques, mica, chert, and unknowns.

e. Sieve No. 300 (polarizing microscope). Rounding; subangular; mineralogy is 75.5 percent quartz, 15.3 percent feldspar, 4.6 percent opaques, 1.8 percent chert, 2.8 percent calcite, and unknowns.

f. Pan fraction (polarizing microscope). Rounding; subangular; mineralogy estimated to be 65 percent quartz, 25 percent feldspar, and 10 percent "heavies" (opaques, zircon, rutile, etc.) and calcite.

Mineralogical summary

7. Table 1 below summarizes the mineralogical composition of the sample and relates this to grain size.

Table 1

Mineralogical Composition

Sieve No.	Ø	mm	Fraction of Total Sample	Percent of Total Sample Quartz	Feldspar	Other*
35	+1.00	0.500	0.050	4.5	0.4	0.1
60	+2.00	0.250	0.450	40.5	3.2	1.4
120	+3.00	0.125	0.465	41.2	5.4	0.5
200	+3.75	0.074	0.021	1.9	0.1	tr
300	+4.40	0.046	0.002	0.2	tr	tr
Pan			0.012	0.8	0.3	0.1
		Totals	1.000	89.1	9.4	2.1

*Other includes calcite, mica, "heavies," and ferromags.

8. The mineralogy of the composite sample may be summarized as: quartz, 89 percent; feldspar, 9 percent; and other minerals, 2 percent. Although no detailed analysis was performed on the heavy mineral suite (specific gravity ≥ 2.8), the apparent low concentration of these minerals (< 2 percent) indicates that the assumed specific gravity of 2.65 is approximately correct.

Particle morphology

9. The degree of rounding is, in part, a function of size; ordinarily the coarser particles exhibit better rounding than the finer ones. This is the case with the Reid-Bedford. Although the coarser particles are classed as subangular to subrounded, the finer particles (less than 0.25 mm) are subangular. The overall classification is subangular to subrounded.

10. With respect to sphericity, the sample consists of considerable prismatic or tabular quartz grains, some of which exhibit sharp edges and conchoidal fracture surfaces. These features are more characteristic of the minus 0.25-mm fraction. The photomicrographs shown in figs. 1-3 illustrate particle morphology (Incls 1-3).

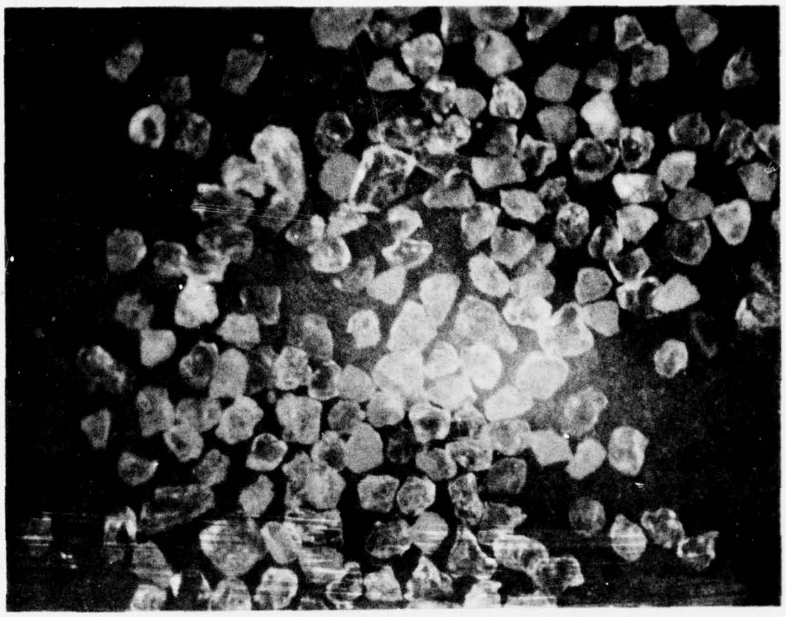
Conclusions and recommendations

11. The Reid-Bedford model sand is classified as: well to moderately well sorted, near symmetrical, very leptokurtic, medium to fine sand whose mineralogy consists of 89 percent quartz, 9 percent feldspar, and 2 percent calcite, ferromags, and "heavies." The rounding class is subrounded to subangular.

12. In order to more adequately determine the degree of rounding, it is recommended that scanning electron microscopy be performed on selected sieve splits in the future.

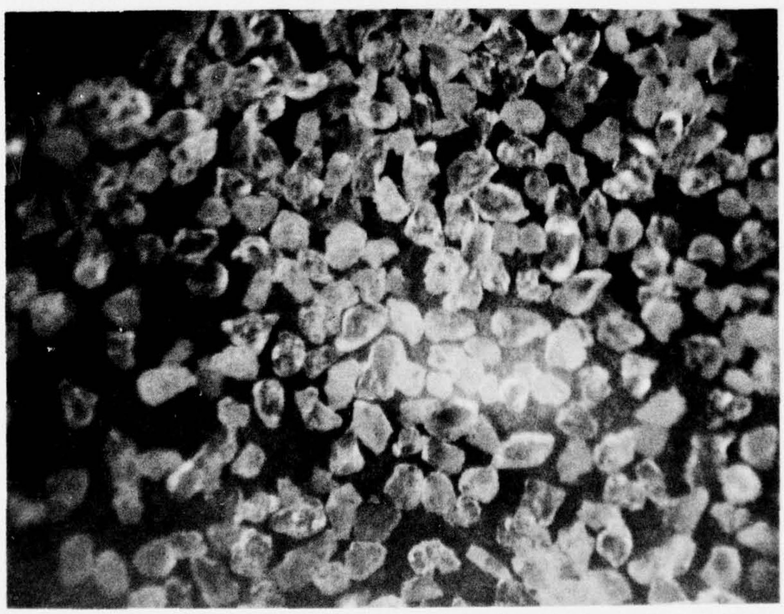
3 *Incl*
as

David M. Patrick
DAVID M. PATRICK
Research Geologist
Engineering Geology Division



(a)

0.25 mm



(b)

0.125 mm

Fig. 1. Photomicrographs of Reid-Bedford sand taken with nonpolarizing microscope: (a) No. 60 sieve and (b) No. 120 sieve.

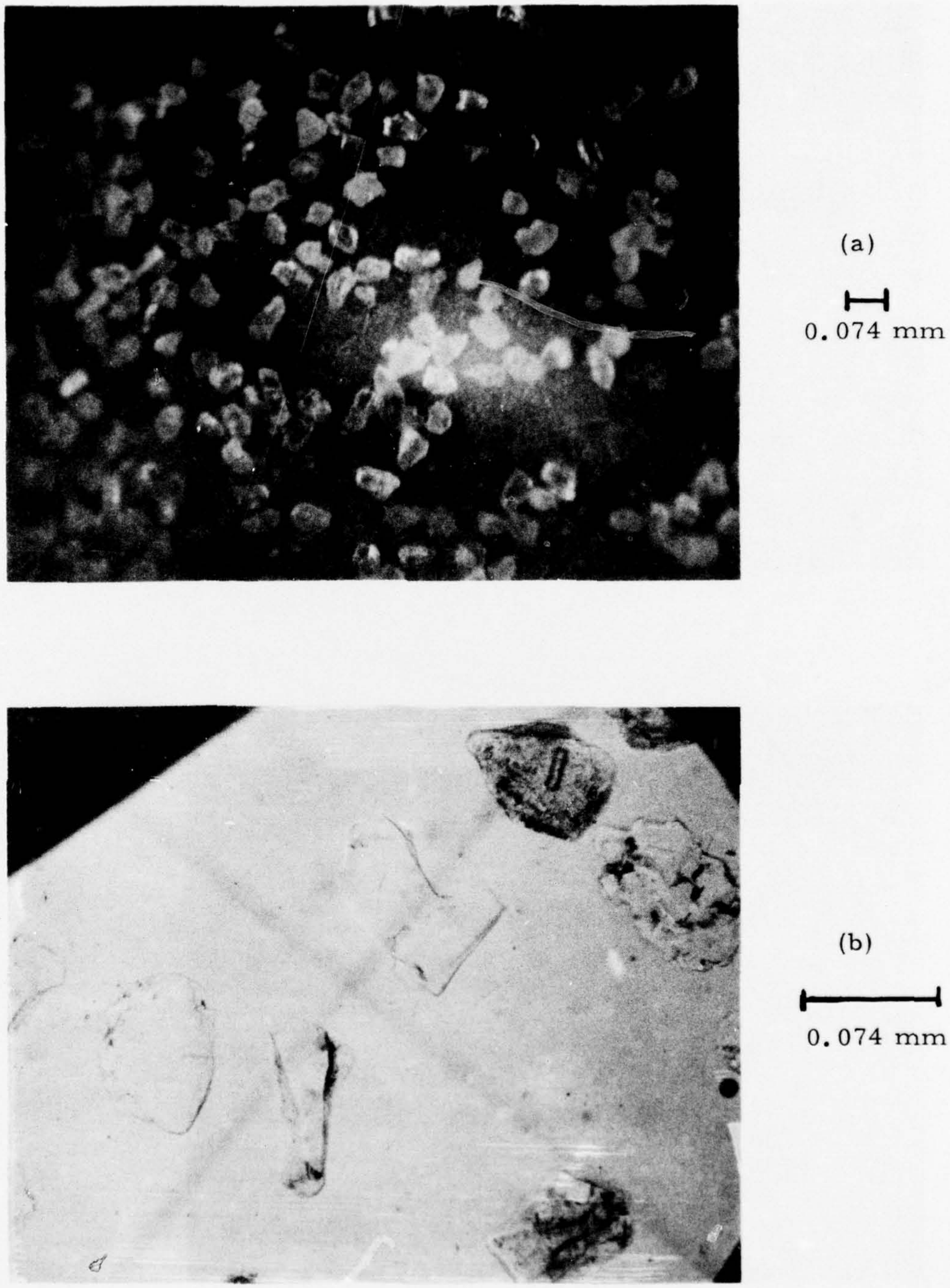
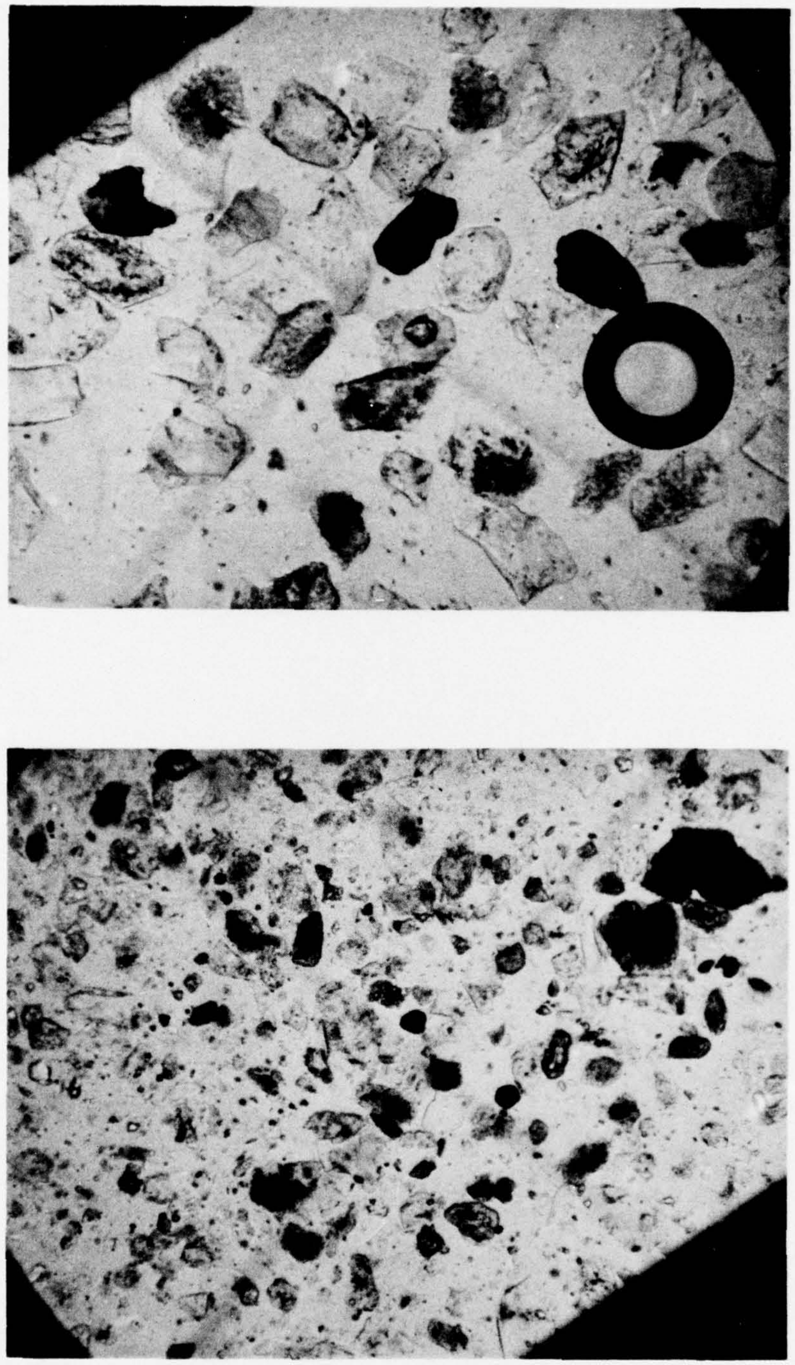


Fig. 2. Photomicrographs of Reid-Bedford sand, No. 200 sieve: (a) nonpolarizing microscope and (b) petrographic microscope, plain light.



(a)

0.046 mm

(b)

0.046 mm

Fig. 3. Photomicrographs of Reid-Bedford sand; petrographic microscope and plain light: (a) No. 300 sieve and (b) passing No. 300 sieve.

APPENDIX B: PETROGRAPHIC EXAMINATION OF OTTAWA SAND

DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION. CORPS OF ENGINEERS
P. O. BOX 631
VICKSBURG. MISSISSIPPI 39180

IN REPLY REFER TO: WESSH

8 July 1975

MEMORANDUM FOR: MR. WAYNE A. BIEGANOUSKY

SUBJECT: Petrographic Examination of Ottawa Sand

General

1. A sample of Ottawa model sand was examined by binocular microscope and its basic statistical parameters were calculated.

Size-distribution statistics

2. Mean and median grain size, standard deviation, skewness, and kurtosis were computed from size distribution analysis. The basic statistical parameters are:

a. Mean grain size: 2.30 ϕ = 0.20 mm, fine sand

b. Median grain size: 2.25 ϕ = 0.21 mm

c. Standard deviation: 0.40 ϕ = 0.76 mm, where well sorted is between 0.35 and 0.50 ϕ

d. Skewness: +0.23 where fine skewed is between +0.10 and +0.30

e. Kurtosis: 1.23 where leptokurtic is between 1.11 and 1.50

Microscopic examination

3. The material retained on the number 60, 120, and 200 sieves was examined under the binocular microscope. The purpose of this examination was to determine gross mineralogy and grain morphology.

a. Mineralogy. The mineralogical composition of this material is estimated to be over 98 percent quartz.

b. Morphology. Generally the coarser grains exhibited better rounding and less angularity than the finer grains. The overall classification is subrounded to rounded. Photomicrographs of the material retained on the number 60, 120, and 200 sieves are shown in Figures 1, 2, and 3, respectively.

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Comparison between Ottawa Sand
and Reid-Bedford Sands

Type of Sand	Mean	Median	S.D.	Skew.	Kurt.	Qz	Rounding
Ottawa	0.20	0.21	0.76	+0.23	1.23	98	+
Reid-Bedford	0.25	0.25	0.71	-0.03	1.54	89	-

4. The statistical, mineralogical and roundness characteristics shown above indicate that the two sands are similar with respect to grain size and over-all sorting. The Ottawa sand, however, consists of relatively more fine-grained particles, has better relative sorting between the tails and central portion of the distribution curve, contains more quartz, and is better rounded than the Reid-Bedford Sand.

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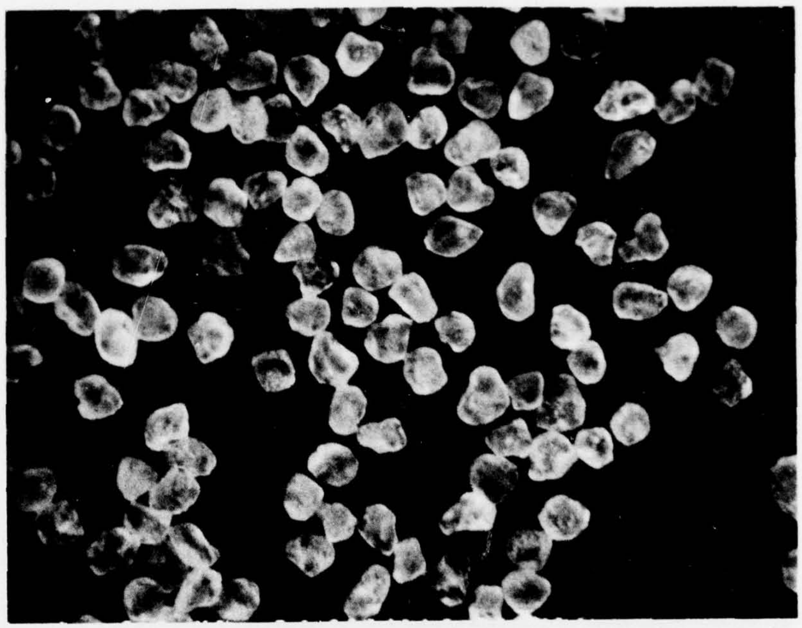
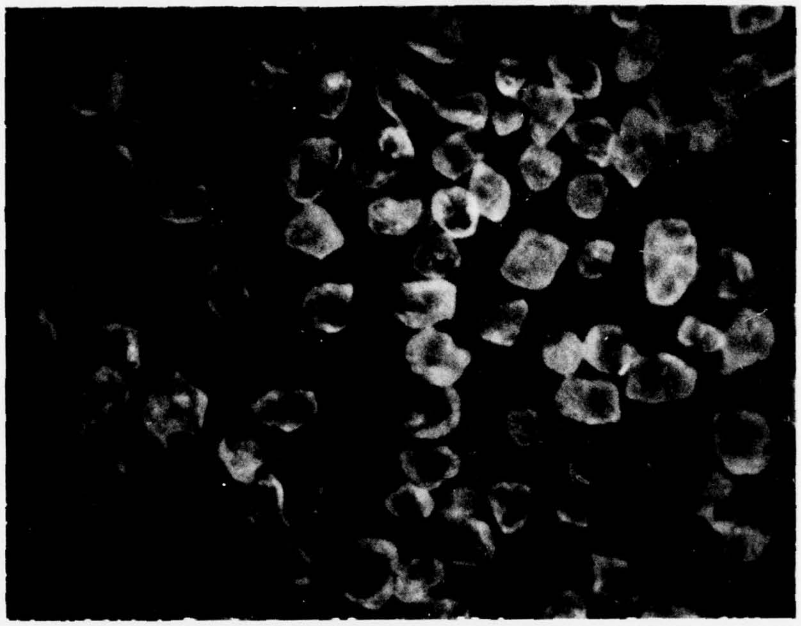
+60



0.25 mm

Figure 1

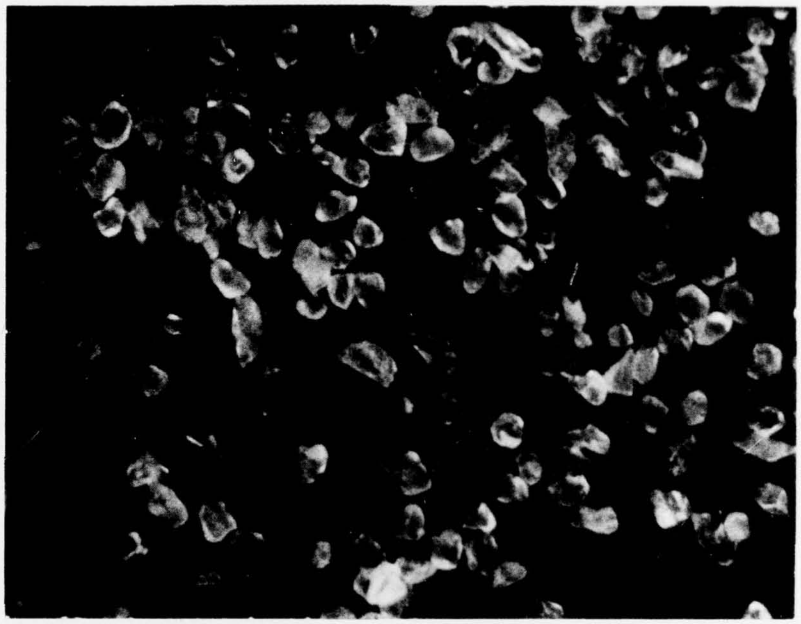
+120



0.125 mm

Figure 2

+200



0.07 mm

Figure 3

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Bieganousky, Wayne A
Liquefaction potential of dams and foundations; Report 1: Laboratory Standard Penetration Tests on Reid Bedford Model and Ottawa sands, by Wayne A. Bieganousky [and] William F. Marcuson, III. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1976.
1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Research report S-76- , Report 1)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C. under CWIS 31145.
Includes bibliography.

1. Dams. 2. Foundations. 3. Liquefaction (Soils). 4. Relative density. 5. Sands. 6. Soil tests. 7. Standard Penetration Test. I. Marcuson, William Frederick, joint author. II. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Research report S-76-2, Report 1)
TA7.W34r no.S-76-2 Report 1